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LUTETIAN ONCOIDAL AND OOIDAL IRONSTONE SEQUENCES; DEPOSITIONAL SETTING AND ORIGIN; NORTHEAST EL BAHARIYA DEPRESSION, WESTERN DESERT, EGYPT

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ABSTRACT:
An unconformity-bounded succession of Lutetian ironstone deposits accumulated along Cenomanian paleohighs in the northeastern plateau of El Bahariya Depression. It represents a reduced section and a facies change of the laterally equivalent thick Lutetian carbonate succession. The ironstone succession is composed mainly of autochthonous/para-autochthonous facies rich in ferriferous ooids, oncoids and various ferruginized skeletal particles. The facies assemblage is organized in two main sequences separated by an intra-Lutetian unconformity (paleokarst). Each facies sequence starts with a tidal flat/lagoonal mud-ironstones with minor silisiclastic mudstones. These pass upward to shoals/megarippled grain- to pack-ironstone facies.

The ferriferous ooids and oncoids are identical in mineralogy, morphology and microfabric. This may strengthen a biogenic role for ooid origin. The ferriferous allochems, matrix and cement consist essentially of amorphous Fe-oxyhydroxides, earthy goethite, hematite and quartz. Earthy goethite admixed with amorphous iron oxyhydroxides represent the precursor materials that were derived from the iron bearing Cenomanian clastics.

The main genetic parameters for the concerned ironstone are: a) synsedimentary supply of amorphous iron; b) slow- to non-deposition; c) *in situ* reworking; d) biogenic encrustation of iron oxide; e) local transportation via megaripple migration; f) emergence and oxidation; g) diagenetic modifications and, h) authigenesis of iron- and manganese- oxides, silica and sulfates. Intermittent phases of uplift and karstification modified the original marine ironstone facies associations and were responsible for the redeposition of iron as cavity filling or laterite products.

Keywords: Lutetian oolitic/oncolitic ironstones, El Bahariya, Western Desert, Egypt, sediment starvation, biogenic ooids, facies analysis.

1. INTRODUCTION

Phanerozoic oolitic ironstones and their genesis have long fascinated many authors, and due to the lack of their modern analogue, numerous genetic models have been introduced but being hitherto debatable (e.g. Young, 1989a, Burckhalter, 1995). Among the Phanerozoic ironstone records, Lutetian oncolitic and oolitic ironstones hosted in carbonate rocks are well represented in three localities in the northeastern plateau of El Bahariya Depression, Western Desert, Egypt, namely: El Gedida, El Harra and Ghorabi (Fig.1).

Since 1903, when Ball and Beadnell firstly reported these ironstones in Gabal Ghorabi as Oligocene lacustrine deposits, its genesis was and still an interesting subject for several geological studies, particularly after the discovery of the commercial ore reserves of El Gedida area in 1961. The current previous interpretation was swinging between two main modes of formation:

a) Syngenetic origin, suggesting a sedimentary accumulation of the iron ore in a lagoon or a lacustrine environment, either contemporaneous with the Middle Eocene carbonate deposition (El Akkad and Issawi, 1963; Said and Issawi, 1964) or during Late Eocene-Oligocene time (Ball and Beadnell, 1903; Hume, 1909; Attia, 1950; El Shazly, 1962)
b) Epigenetic origin, attributing the ironstone formation to either metasomatic replacement of the Eocene carbonates by an iron bearing ascending Oligo-Miocene hydrothermal solutions (e.g. Gheith, 1959; El Hinnawi, 1965; Basta and Amer, 1969; Tosson and Saad, 1974; El Sharkawi *et al.*, 1987), or due to weathering and diagenetic alteration of the Eocene carbonate or glaucony facies by descending Fe-rich drainage water (El Sharkawi and Khalil, 1977). Kamel (1971) and El Bassyony (1984) also suggested a combination between lagoonal deposition and subsequent enrichment by hydrothermal solutions.

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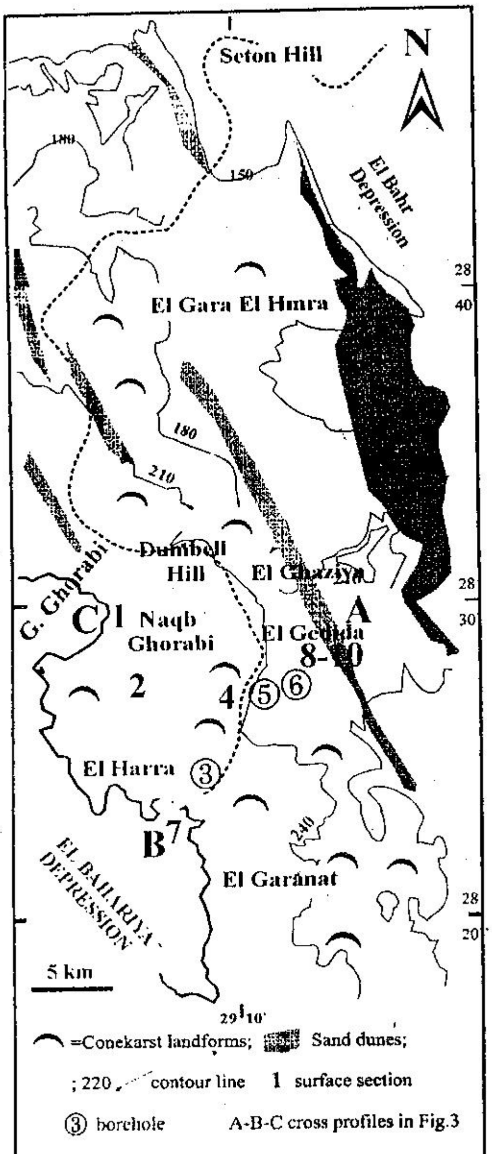
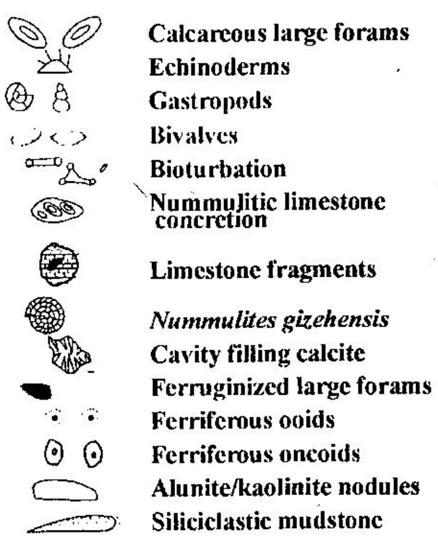


Fig. (1): Location Map

Symbols Used In The Measured Sections



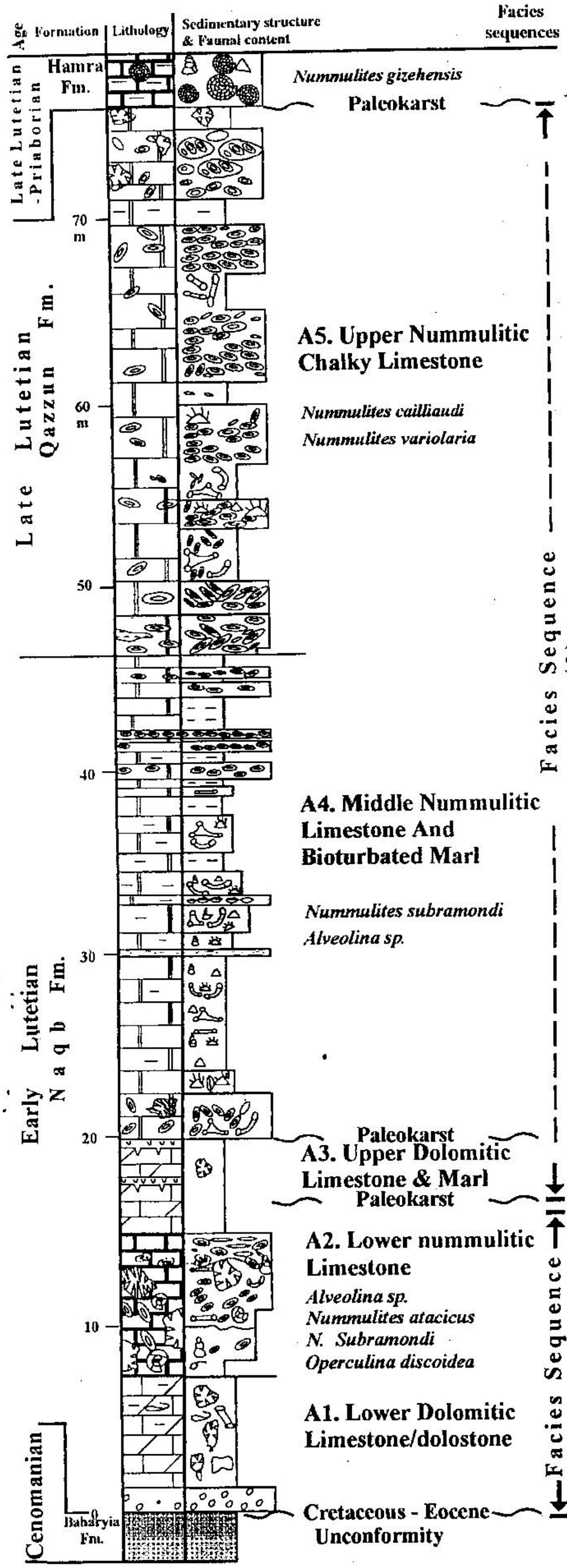


Fig. (2): Composite Stratigraphic Section And Facies Sequences Of The Lutetian Carbonates

According to El Aref and Lotfy (1989), El Bahariya Eocene iron ore represents ferricrete duricrusts and karstic ferruginous deposits. Recently, El Aref *et al.* (1999) recognized five genetic types of Eocene ironstones, being: a) stratabound lateritic ironstone confined to Eocene-Cretaceous unconformity, b) stratiform shallow marine oolitic-pisolitic ironstone, c) stratiform lagoonal ferruginous dolostone and mudstone, d) karst ore, and e) stratiform ore conglomerates. These authors emphasized the importance of the paleotopography, paleoclimate and paleoenvironments in the accumulation of these ore types during the Lutetian time span in their sites of formation.

Whereas, much of the previous genetic interpretations were based on mineralogy and geochemistry, a little emphasis has been given to the role of sedimentology, facies analysis and diagenesis of both ironstones and the equivalent carbonate rocks. The present work tends to elucidate the original depositional facies of El Bahariya Lutetian ironstones (iron ore), and to recognize their primary composition, fabrics, structures, facies hierarchy, mode and site of deposition. Post-depositional modifications involving karstification and lateritization and mineral paragenesis are also addressed, and a genetic model is constructed.

Representative stratigraphic successions of the ironstones and the neighbouring carbonates are compiled from discrete surface sections and five boreholes drilled in the south border of El Gedida mine (Fig.1). The Lutetian ironstones are studied in detail and sampled from El Harra scarp and El Gedida mine. The most representative profiles are measured along the Eastern Wadi area (geographic name in El Gedida mine) and at the upstream of Wadi El Harra (at Naqb El Harra scarp).

2. GEOLOGIC SETTING

The Bahariya depression has a large oval shape that was naturally excavated in the Western Desert at about 320 km, SW of Cairo. It is enclosed from all sides by plateau of Eocene carbonates with, and locally without Upper Cretaceous rocks. Its floor and surrounding scarps are mostly made up of Cenomanian clastics. The study area is the southern reach of the northeastern plateau of this depression (Fig.1). The area is a typical karst terrain dominated by conehills with cockpits and discrete depressions of which, El Gedida, Ghorabi and El Harra are the most pronounced. These three depressions which host the concerned ironstones are excavated within Eocene and locally Oligocene rocks resting upon anticlinal folds of Cenomanian clastics. Whereas, El Gedida is a closed depression within the plateau, the other two depressions are opened to the main Bahariya depression. However, each of these depressions is characterized by a central elevated hills or inselberg (e.g. Ghorabi inselberg and Lion hills in El Gedida mine area), being partially or completely surrounded by annular or semicircular valleys.

Structurally, the distinct wrench deformation affecting the Bahariya depression extends also in the study northeastern plateau (Sehim, 1993). A series of double-plunging anticlines and synclines being arranged in an *echelon* pattern along NE- dextral wrench faults (Ghorabi & El Harra faults) are reported (Sehim, 1993 and Iron Exploration Project IEP, 1993-1997). The wrench deformation prevailed in Late Cretaceous and occasionally re-activated during Late Eocene. Ghorabi, Dumbell, El Ghaziya, El Gedida and El Harra domes and anticlines are the most pronounced examples of the wrench-related folding.

3. LITHOSTRATIGRAPHY

In the study northeastern plateau, the Lutetian sedimentary deposits are widely distributed and exhibit distinct lateral changes in both facies and thickness. The Lutetian succession is represented mainly by open marine carbonates (70- 80 m thick) and locally by ironstones (10-15 m thick). It invariably oversteps different stratigraphic horizons of the Cenomanian Bahariya Formation and underlies either the fossiliferous marl or the glauconitic ironstone and green sand of the Hamra Formation (Late Lutetian- Priabonian).

I. Lutetian Carbonate Succession

The widely distributed Lutetian carbonate succession consists essentially of karstified pinkish to yellowish gray limestone, dolostone and marl (Naqb Formaton of Said and Issawi, 1964), grading in the upper part to snow white chalky limestone with characteristic horizons of melon-sized hard silicified limestone concretions (Qazzun Formation of Said and Issawi, opcit.). Most of these rocks are crowded with nummulitids, alveolinids and various megafossils.

The present authors could differentiate the Lutetian carbonate succession (Naqb and Qazzun formations) into five distinct stratigraphic units (Fig. 2), which can be easily traced allover the study area, and can be correlated with their equivalent units of the

ironstone succession. These units are, from base to top:

1- Lower dolomitic limestone and dolostone (5-10 m)
It is composed of very thick, massive to bioturbated nodular beds of dolomitized lime mudstone. Its basal part is slightly glauconitic and contains scattered quartz pebbles, mud clasts, phosphatic- and ironstone- glaebules. This unit is poorly fossiliferous except a thin streak of oyster hash, which occurs near its middle part (Fig.2).

2- Lower nummulitic limestone (4-6 m)
It is a marker unit allover the study area, and is characterized by a thoroughly bioturbated to massive bedded nummulitic limestone; crowded with *Nummulites atacicus, Operculina discoidea, N. subramondi* with *Alveolina sp.* admixed with diversified megafossils. This unit is truncated by a distinct paleokarst surface with superimposed pedogenetic features (Fig.2).

3- Upper dolomitic limestone and marl (5-10 m)
This unit forms minor and stepped escarpments that resulted from the northward retreat of the main northeastern scarp of El Bahariya depression. It is formed of poorly fossiliferous dolomitized lime mudstone with discontinuous very thin bands of evaporites. The beds are almost massive to fine-laminated with desiccation cracks, *in situ* brecciation, and fracture filling *terra rosa* and blocky calcite (Fig.2).

4- Middle nummulitic limestone and bioturbated marl (20-25 m)
It builds up the upper part of the Naqb Formation. Its outcrops are commonly in the form of conehills with cockpits, which litter the plateau surface between El Gedida and Ghorabi areas. It is formed of well bedded and bioturbated fossiliferous limestone and marl, intercalating with nummulitic and alveolinid banks. The carbonate beds commonly show karst dissolution features, and their original grayish white to yellow colours are almost masked by remarkable pink, violet and red surficial tarnish.

5- Upper nummulitic chalky limestone (30 m)
This unit constitutes the bulk of the Qazzun Formation; which its best outcrops occur in the footslope of El Gara El Hamra (Said and Issawi, 1964). Southward, in the district between El Gedida, Ghorabi and El Harra, this unit was almost eroded, except few meters being locally preserved as indurated hard cap for some discrete hills of the Naqb Formation. The unit has a distinct snow white tone, and consists of alternating chalky lime mudstone and nummulitic banks flooded with *Nummulites cailliaudi, N. variolaria* with molluscan and echinoderm fossils (Fig.2).

II. Lutetian Ironstone Succession
At El Gedida, Ghorabi and El Harra areas, the above-described thick Lutetian carbonate succession is replaced by a very reduced section (10-15m thick) of ironstones (Fig.3). Such ironstone succession is bounded and internally punctuated by unconformities with superimposed karst and pedogenetic features (Figs.4&5). Thick intervals of the carbonate units (almost of units 4 and 5, Figs.2&3) are entirely missed or not represented by comparable ironstone facies. However, many of the faunal assemblage, especially nummulitids and alveolinids do exist. At some places along the borders of the ironstone hosting localities, only the lower part of the Naqb carbonates (units 1&2,Fig.2) changed into ironstone facies, resting unconformably below carbonate beds (e.g. Naqb Ghorabi section no.1, Figs.1&3). Intertonguing between carbonate and ironstone beds is also reported in borehole no. 6 (southern border of El Gedida mine, Fig.3). In El Gedida mine and Naqb El Harra scarp, the Lutetian ironstone succession is well developed and best preserved. It oversteps the Cenomanian Bahariya clastics and is erosively truncated by the Upper Eocene glauconitic ironstone and glaucony facies of the Hamra Formation (Figs.4&5). The upper unconformable contact has scouring relief reaching to 5 m, and is commonly with suprajacent conglomerates of locally reworked ironstone gravels as well as reworked nummulitids and silicified limestone nodules (Fig.5).

The most representative section of the concerned ironstones is measured from the recently excavated mine faces of the Eastern Wadi area of El Gedida mine (Fig.5). In this area most of the original ironstone facies and their depositional fabrics and structures are well preserved, while in other sections, these are almost obscured, via intensive replacement by late diagenetic crustified hematite and goethite (karst infilling). The original ironstone succession is differentiated into four distinct stratigraphic units, being from base to top:

1- Lower variegated mud-ironstone (0.2-1.5 m)
This unit is well developed along the Cenomanian-Lutetian unconformity surface (= type 2 lateritic ironstone of El Aref *et al.*1999), and is stratigraphically correlatable with the basal dolomitic limestone unit (unit 1) of the carbonate succession (Fig.3). It varies in thickness from few

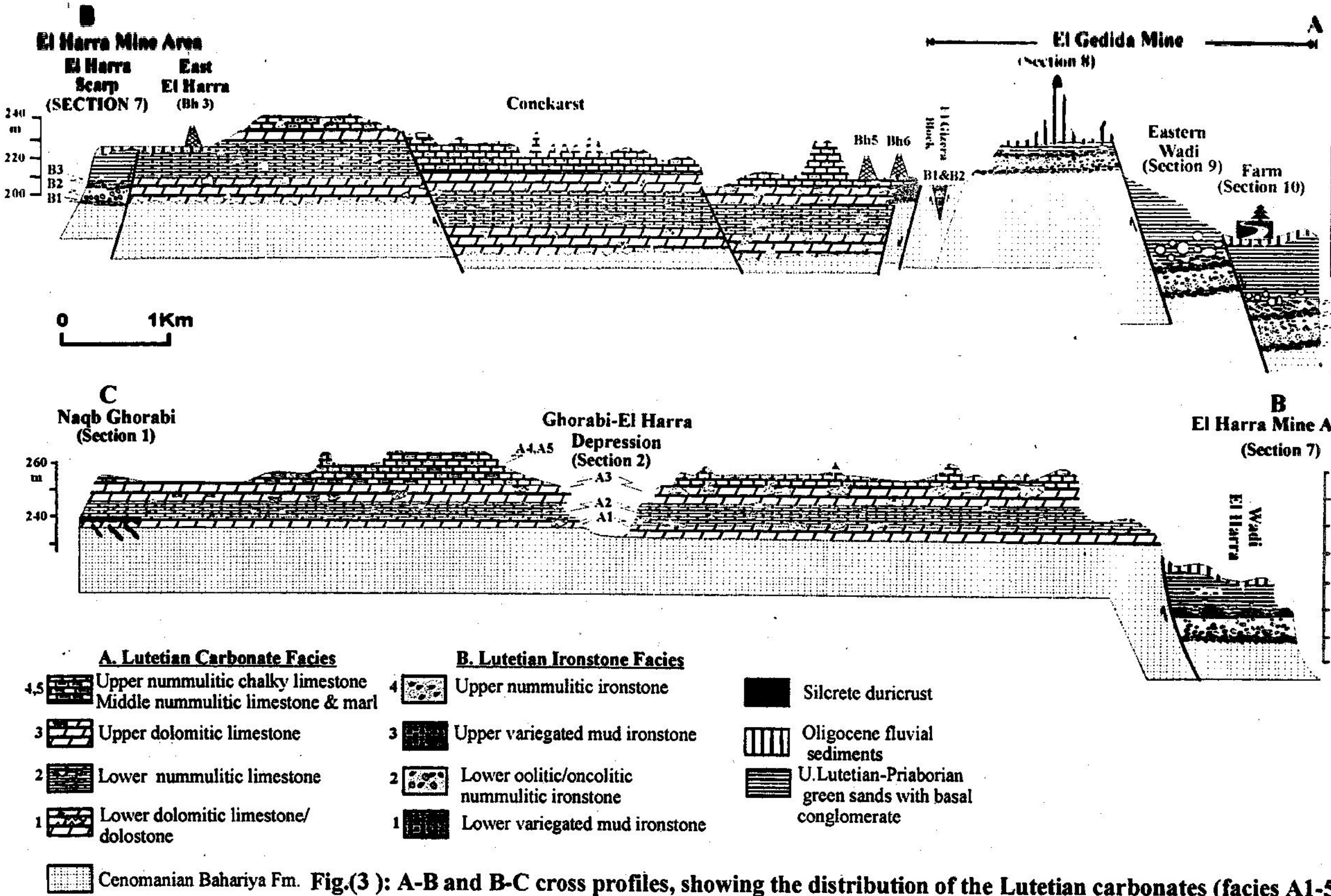


Fig.(3): A-B and B-C cross profiles, showing the distribution of the Lutetian carbonates (facies A1-5) and their lateral changing to ironstones (facies B1-4), Northeastern Plateau, El Bahariya Depression

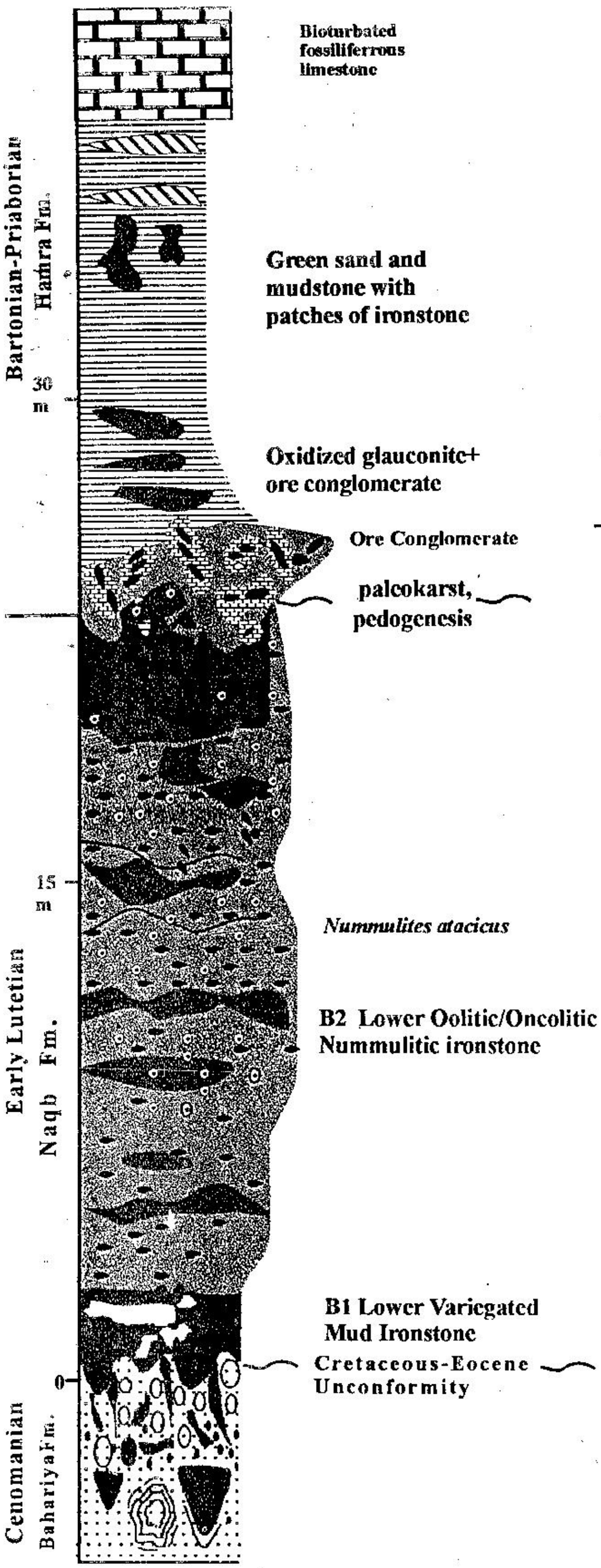


Fig (4) : Fine Lithostratigraphy Of The Lutetian Ironstones At The Upstream Of Wadi El Harra, El Harra Mine Area (section number 7).

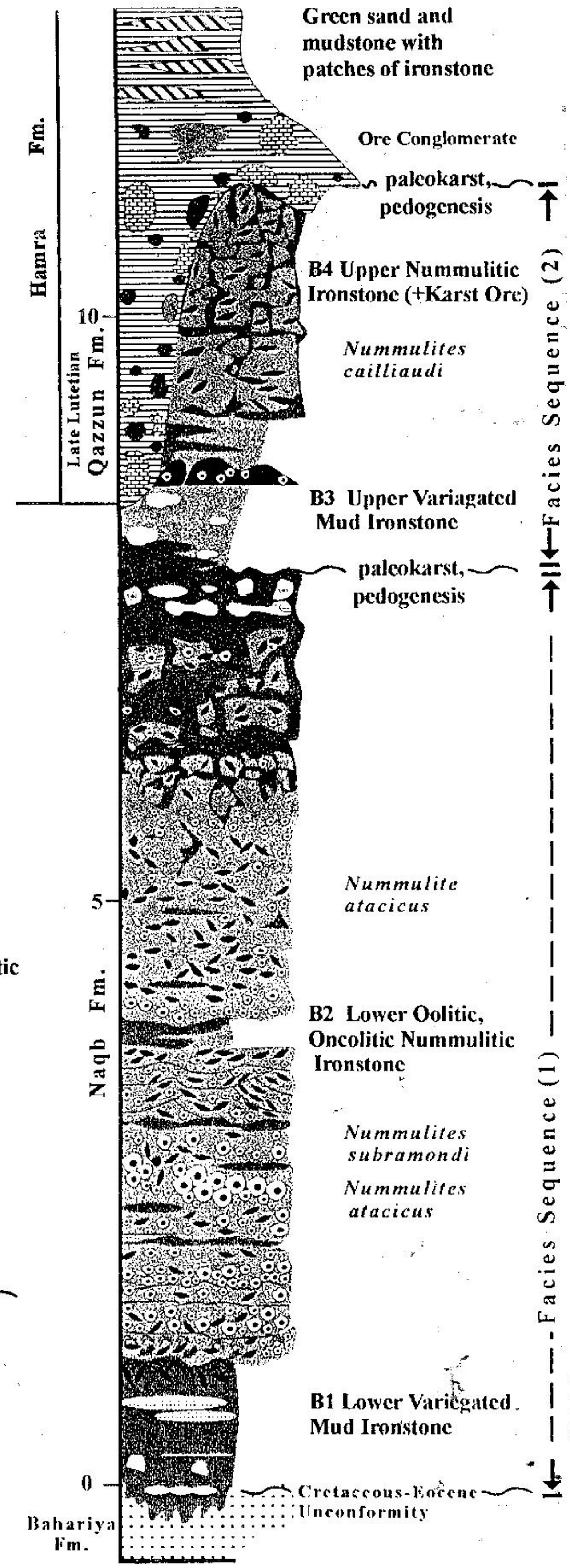


Fig (5):fine Lithostratigraphy Of The Lutetian Ironstones At The Eastern Wadi Area Of El Gedida Mine (section number 8)

centimeters up to 1.5 m. Such variation is almost related to the paleorelief of the Cretaceous-Eocene unconformity surface and the erosive nature of the overlying nummulitic ironstone beds. It is composed mainly of reddish brown, brick red and yellow ochreous muddy ironstone intertonguing with each other and with few thin lenses of iron-stained kaolintic and alunitic mudstone (Fig.5). In Naqb Ghorabi section, the lower variegated mud ironstone attains 75 cm thick; representing a transition between the ironstone and carbonate facies where it consists of egg-yellow and brown ferruginous glauconitic marl.

2- Lower oolitic, oncolitic and nummulitic ironstone (1.5-6 m)

It is the most pervasive and thickest ironstone unit, being recorded in almost all ironstone-hosting localities (= the oolitic-pisolitic ore type no. 3, of El Aref *et al.*, 1999). It is equivalent to the lower nummulitic limestone unit no. 2 of the carbonate succession (Fig.3). Its greatest thickness (? 6m) is measured at the Eastern Wadi area of El Gedida mine and at El Harra section (Figs.4&5). At Naqb Ghorabi, it is remarkably reduced to about 1.5 m thick, and is unconformably overlain by carbonate succession. The unit consists mainly of medium- to thick nummulitic ironstone beds (10-30 cm thick, for each), which swell and pinch laterally. The beds are very rich in ferruginized nummulitids with some alveolinids, operculins, bioclasts of megafossils and abundant ferriferous ooids, oncoids and peloids (Fig.5). Discontinuous thin layers and laminae of ochreous mud-ironstone commonly exist along the irregular contacts of the main nummulitic/oolitic ironstone beds. The upper unconformable boundary of this ironstone unit is demarcated by distinct paleosol features, which are also traced along the top surface of unit 2 of the surrounding carbonate succession. The pedogenetic features include: a) crackle and collapse breccia of poorly sorted, cavernous and leached rubbles; b) frequent mouldic cavities and dissolution voids and channels, being partially to completely filled with illuviated; and c) infiltrated insoluble residues and exotic particles. Kaolinitic and alunitic nodules, being in places coalesced to form enterolithic-like lenses are common. A cockade structure consisting of rotten rubbles that are coated by colloform iron oxide crusts is also recorded.

3- Upper variegated mud-ironstone (0.2-1.5 m)

It is another non-fossiliferous ironstone unit, existing only in the Eastern and Western Wadi areas of El Gedida mine, and is totally eroded from other ironstone hosting localities (Fig.3). Its contacts with the encompassing stratigraphic units are unconformable. This unit underlies either the upper nummulitic ironstone unit with a system of discrete open caves aligned along the boundary or is directly truncated by the glauconitic ironstone and glaucony facies of the Hamra Formation. It is closely identical, in both lithology and bedding nature, to the lower variegated mud-ironstone unit (Figs.4&5). The stratigraphic position of this ironstone unit overlying the level of *Nummulites atacicus* is probably comparable to a thick interval comprising units 3 and 4 of the adjacent carbonate succession (Fig.3). The reduced thickness and the unconformable boundary surfaces of this ironstone unit may suggest that, its site of formation received very little sediments or subjected to intermittent periods of non-deposition and erosion.

4- Upper nummulitic ironstone unit (0-3 m)

This unit is only recorded in the Eastern Wadi area of El Gedida mine. The preserved thickness varies from face to face even in the same mining block. It is completely eroded in the other adjacent areas of El Gedida mine as well as in El Harra and Ghorabi locatities (Fig.4). It was described as karstified ferruginous mudstones and dolostones being dominated by karst solution features and residual karst products (El Aref and Lotfy, 1989 and El Aref *et al.*, 1999). Its occurrence is controlled by the scouring magnitude of the erosional surface separating the Lutetian ironstones from the overlying Upper Eocene Hamra Formation. The unit is composed of thick-bedded nummulitic ironstone rich in mouldic cavities and ferruginized tests of the large sized *Nummulites cailliaudi* with some gastropods and pelecypods. Scattered silicified and ferruginized nummulitic limestone nodules and boulders, having spherical to ellipsoidal form and reaching occasionally to a "melon" size, are a marker feature in this unit. The beds of this unit are highly deformed into mesoscopic tight folds and are mostly crackled into discrete rubbles floating in ochrous matrix (Fig.5). This ironstone unit with its contents of *Nummulites cailliaudi* and silicified limestone nodules may represent a reduced accumulation being equivalent to some stratigraphic intervals of the carbonate unit 5 (Qazzun Formation) of the adjacent carbonate succession (Figs.2&5).

4. IRONSTONE FACIES ANALYSIS

The study Lutetian ironstones comprise a number of grain- and mud-supported facies, which are defined relying on the type and content of ferriferous allochems as well as the depositional fabrics and structures. The facies characteristics and the

depositional criteria are analyzed and recognized from both microscopic and field investigations.

I. Ironstone Facies Particles

The various types of the recorded ferriferous allochems could be ranked into three main categories, being in descending order of abundance: ferruginized skeletal particles, ferriferous coated grains and ferriferous peloids and intraclasts.

1- Ferruginized skeletal particles (Pl.1)

These are the essential allochems of the study ironstone facies. They occur as free components or form the cores of most ferriferous-coated grains. The pervasive particles are tests and molds of nummulitids, alveolinids with body fossils of gastropods, bivalves, echinoids and benthic algae (Pl.1A-E). Microbial remains also exist, but being less common. The original calcareous skeletal particles are completely replaced by dark brown and golden yellow amorphous iron oxyhydroxides mixed with fine goethite and hematite particulates and crystals and in parts by quartz. The original morphological features and internal architectures of many particles are still preserved. The diagnostic fibrous wall structure of the nummulitic tests and the erect algal cells or filaments are commonly pseudomorphosed by acicular prisms of goethite (Pl.1A, F&G). The benthic algal/microbial remains have almost elongated fusiform or cylindrical shape (Pl.1E). The majority possesses a central enterolithic-like vesicular zone (Pl.1F), terminating with flaring or denderitic threads and is often encrusted by wavy rows of erect to sinuous prismatic ferruginous filaments (Pl.1F&G). Lumps and mesh forms of tuberous microbial remains with tubes having circular or polygonal outlines are also observed (Pl.2A-C). Also, many of the nummulitids and molluscan particles show abundant microborings of endolithic algae and/or fungi (Pl.2D).

2- Ferriferous coated grains and ooids (Pls. 2E-H&3)

The term coated grains (Wolf, 1960) include the concentrically formed grains other than ooids. Based on grain size, grain morphology, internal fabric and inferred mode of formation, the encountered-coated grains are differentiated into the following types:

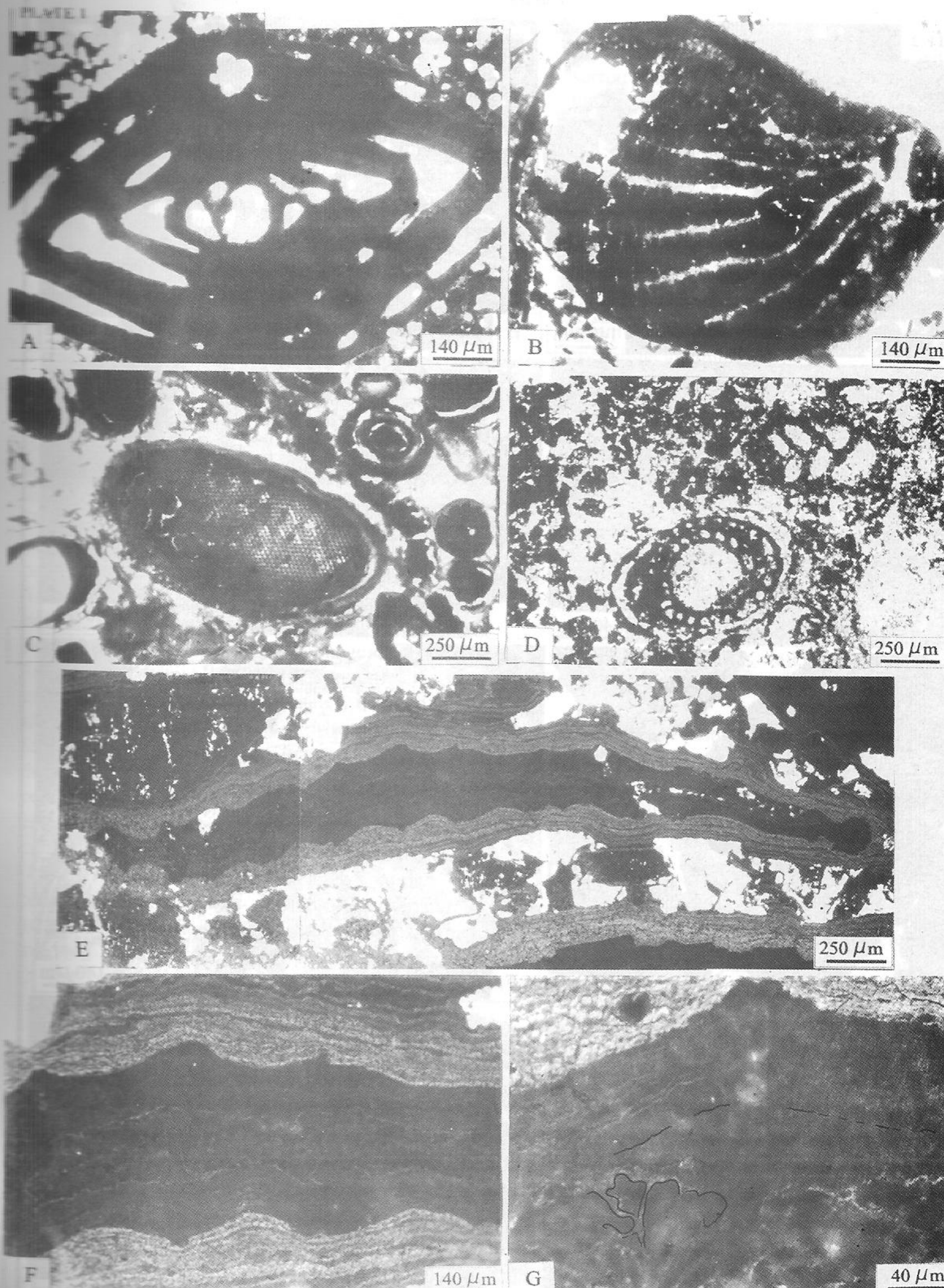
a- Ferriferous oncoids and ooids

Ferriferous oncoids (biogenically encrusted grains) and ooids commonly coexist together and are best developed in the study ironstone facies, particularly in the Eastern Wadi area of El Gedida mine. In El Harra section, ooids are more pervasive than oncoids, and some layers consisting entirely of ooids are recorded. Except of the 2-mm size boundary, both ooids and oncoids are identical in mineralogy, grain morphology and more or less in the internal organization (Pl.2E&F). The majority has discoid and ellipsoidal forms, and less frequently being spherical. They mostly conform the shape of their internal cores. Large oncoids commonly exhibit bumpy, botryoidal, box or nipple-like forms. Internally, the oncoids and ooids possess either ferruginized skeletal or non-skeletal nuclei (Pl.2E). They also vary from types with a thick and multi-laminated cortex to grains having a thin and faintly laminated envelope. The non-skeletal cores are commonly ferruginous peloids and angular clasts of mud-ironstone, and less frequently being formed of pre-existing ooids, parts of ooids, oncoids and oolitic rock fragments (Pl. 2E & Pl.3B).

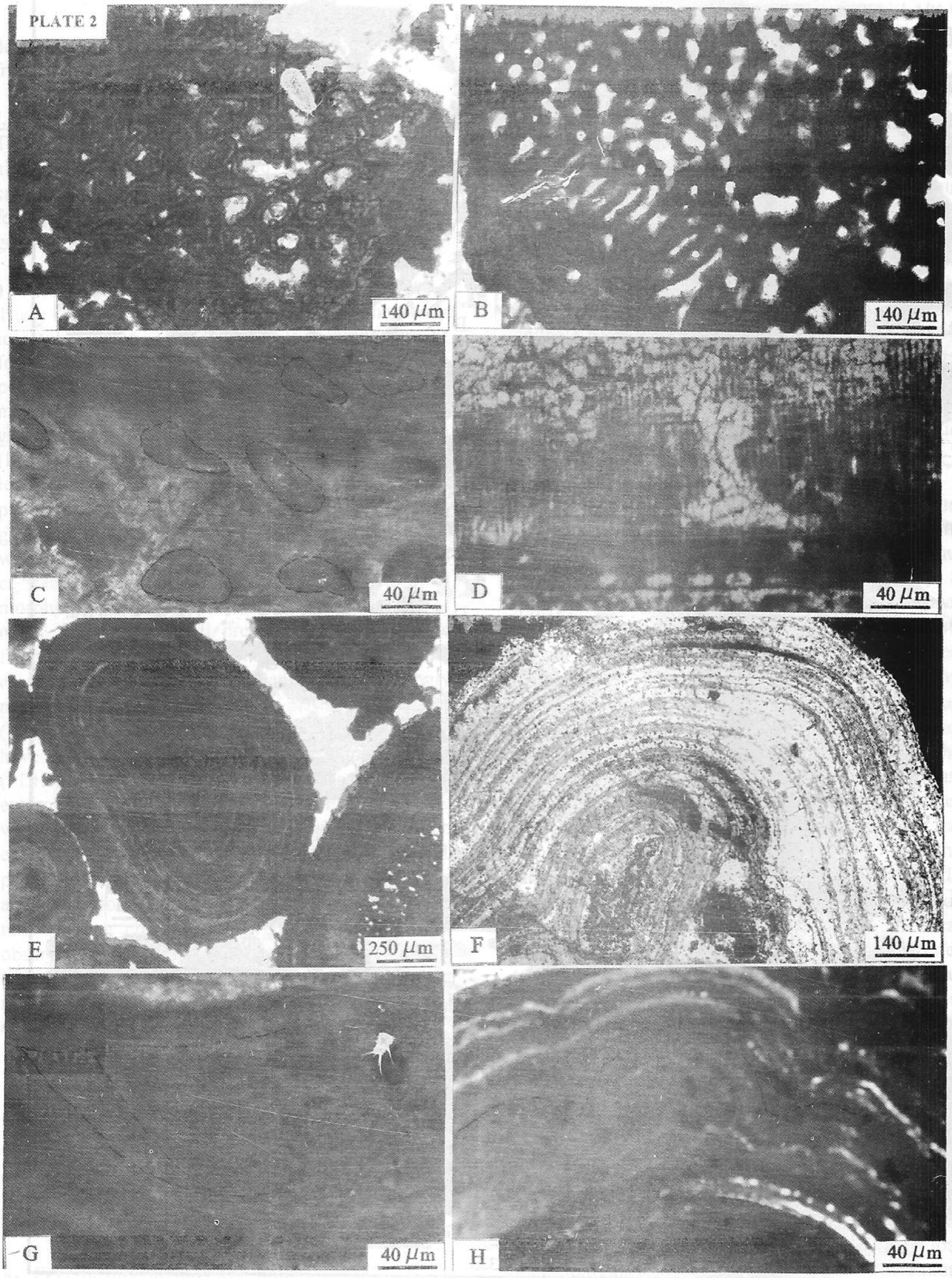
The cortical envelopes of almost all ooids and oncoids consist mainly of two order of lamination. The first order is the principal and primary (syn-depositional) laminae. It is characterized by a superposition of doublet made up of light brown laminae with faint greenish tint overlain by a dark brown one (Pl.3B). These laminae are composed mainly of amorphous iron oxyhydroxides and earthy goethite. The variation in their tone is probably due to a difference in organic matter or amorphous iron oxyhydroxides that increase in the dark laminae. The alternation of these laminae is not always rigorous, and their geometry and ultrastructure vary either from grain to grain or even at different levels of the same grain. In most ooids and small oncoids, the laminae are almost continuous, planar to slightly wavy and rather isopachous (Pl.2E). In large oncoids and macroids, particularly in the external cortical zone, most laminae are non-isopachous, sometimes truncating and overlapping each other (Pl.2G) and grade from slightly curved to strongly sinuous, giving rise to a club-shaped or knobby microstromatolitic structure (Pl. 2H). Some of these irregular laminae incorporated small ooids or ooid fragments (Pl.3A).

Ultrastructurally, the light and dark primary laminae are apparently massive or thrombolitic, but actually exhibit an internal laminatiom. These ultra-fine second order laminae consist of a set of dark films, which may compact together until they may lose their individuality. The second order films are more distinct in the dark primary laminae, particularly when their original amorphous iron composition is diagenetically replaced by crystalline goethite, and the residual impurities concentrate and delineate the fine films (Pl.2F).

PLATE 1



PL 1: Ferruginized skeletal particles. A) A ferruginized *Nummulites*, preserving its diagnostic fibrous wall structure, PPL. B) A ferruginized *Alveolina*, preserving its internal archetecture, PPL. C) A ferruginized echinoid plate shows the characteristic porous structure, PPL. D) Ferruginized and partially silisified benthic forams of miliolids and biserial tests, PPL. E) A ferruginized skeletal alga exhibiting elongate fusiform shape, PPL. F) An enlarged part of (E) shows a central entirolithic-like vesicular zone of the skeletal algae, PPL. G) An enlarged part of (F) showing the encrusted wavy rows of erects prismatic algal filaments, PPL.



Pl. 2: Ferruginous microbial structures. A-C) Lumps of different ferruginous microbial tubes, PPL. D) A microbored ferruginized skeletal particle, PPL. E&F) Ferriferous ooids and composite oncoids; both are identical in mineralogy, morphology and internal organization of isopachous cortical laminae, thin & polished sec., PPL. G) An enlarged part of oncoid cortex shows truncation and onlapping of cortical laminae, PPL. H) Sinuous cortical laminae displaying microstromatolitic-like structure in oncoid cortex, PPL.

b- Ferriferous cortoids

Ferriferous coated grains similar to the calcareous cortoids of Flügel (1982) are encountered in the study ironstone facies, especially from El Harra ironstone deposits. They commonly admix with ferriferous ooids and oncoids, and consist mainly of microbored ferruginized bioclasts enveloped by a thin and unlaminated rind of amorphous iron oxyhydroxides. This single envelope is usually non-isopachous and has an irregular contact with the internal bioclasts. These ferriferous cortoids may represent an early stage of ooid and oncoid formation.

c- Ferriferous concretionary glaebules

Concretionary glaebule is a three-dimensional pedological grains having a spherical to irregular form and a general concentric and or convolute laminated fabric about a center, a line or a plane (Brewer, 1964). It is comparable to the vadose pisoids of Dunham (1969) and to the well-defined nodules and pisolitic concretions of Nahon (1995). This type of coated grains is best developed in the base of the ironstone unit 2 in the Eastern Wadi section (Fig.5). Such concretions range, in size, from 1mm up to 1 cm. They have commonly elongated ellipsoidal form, which is intimately directed by the shape of the nucleus (Pl.3C). Most grains possess ferruginized skeletal nuclei, being almost of tests of the large benthic forams and algal remains. A faint concentrically laminated envelope consisting essentially of continuous bright orange goethite laminae encasing discontinuous dark brown threads (Pl.3C) surrounds the skeletal cores. The concretionary glaebules differ than ferriferous oncoids by the following distinct features, which may point to a different mode of formation:

i) The cortical laminae of the glaebules are highly irregular, crinkled, convoluted and with sharp angular terminations (Pl.3D). Such geometry contrasts with the relatively smooth, curved and subrounded laminae of the oncoids and ooids (Pl.2F), and reflects neither a mechanical accretion nor a biogenic encrustation.

ii) The cortical laminations usually exhibit a polarity in the development, being preferentially thicker at the edges or corners of the glaebules.

iii) The adjacent concretionary glaebules currently display a polygonal fitting of their outer laminae.

iv) There is a remarkable reverse relationship between the size of the core and the surrounding cortex. The latter appears to be gradually developed at the expense of the interior core (Pl.3C). This gradual degradation of the nuclei could be indicated by their corroded margin, from which, there are microscopic scales and clots being just detached and incorporated within the surrounding goethitic cortical laminae. However, the liberated clots are still aligned in concentric but discontinuous lines, representing the traces of the successive inward recessed margin of the consumed core (Pl.3C).

v) The boundary between the clotted lines of the nucleus remnants and the invading goethite zones of the grown cortex is hazy and highly corroded. In some parts of the cortex, the clotted lines are also digested by goethite, and these parts became unlaminated and appear as thick massive zone of crystalline goethite (Pl.3E).

The above listed features characterize the coated grains that are diagenetic in origin and *in situ* formed through pedogenetic glaebulization processes (Nahon, 1991). These orthic glaebules or orthic pisoids were developed via a gradual and centripetal transformation to goethan or neogoethan for a dissected pre-existing ironstone rock or ferriferous particles. Its essential composition was originally of dark brown amorphous Fe oxyhydroxides. The centripetal replacement started from irregular microscopic cracks as well as from intra- and inter-particles pore spaces.

3- Ferriferous peloids and intraclasts

These are internally massive ferriferous grains, occurring as free constituents or form the cores of the different types of coated grains. They are composed of dark brown to yellow amorphous Fe oxyhydroxides with goethite and occasionally hematite. Most peloids are rounded to subrounded and are internally cracked. The majority of which seems to be developed from a complete masking of bored bioclasts via ferrugination in a manner similar to the formation of the Bahamite calcareous peloids of Flügel (1982) in carbonate facies. Few of these ferriferous peloids still preserve traces of the original skeletal microstructures. The ferriferous intraclasts are almost angular to subangular and mostly made of mud-ironstone rock fragments with some particles being derived from oolitic and bioclastic-oolitic ironstone rocks.

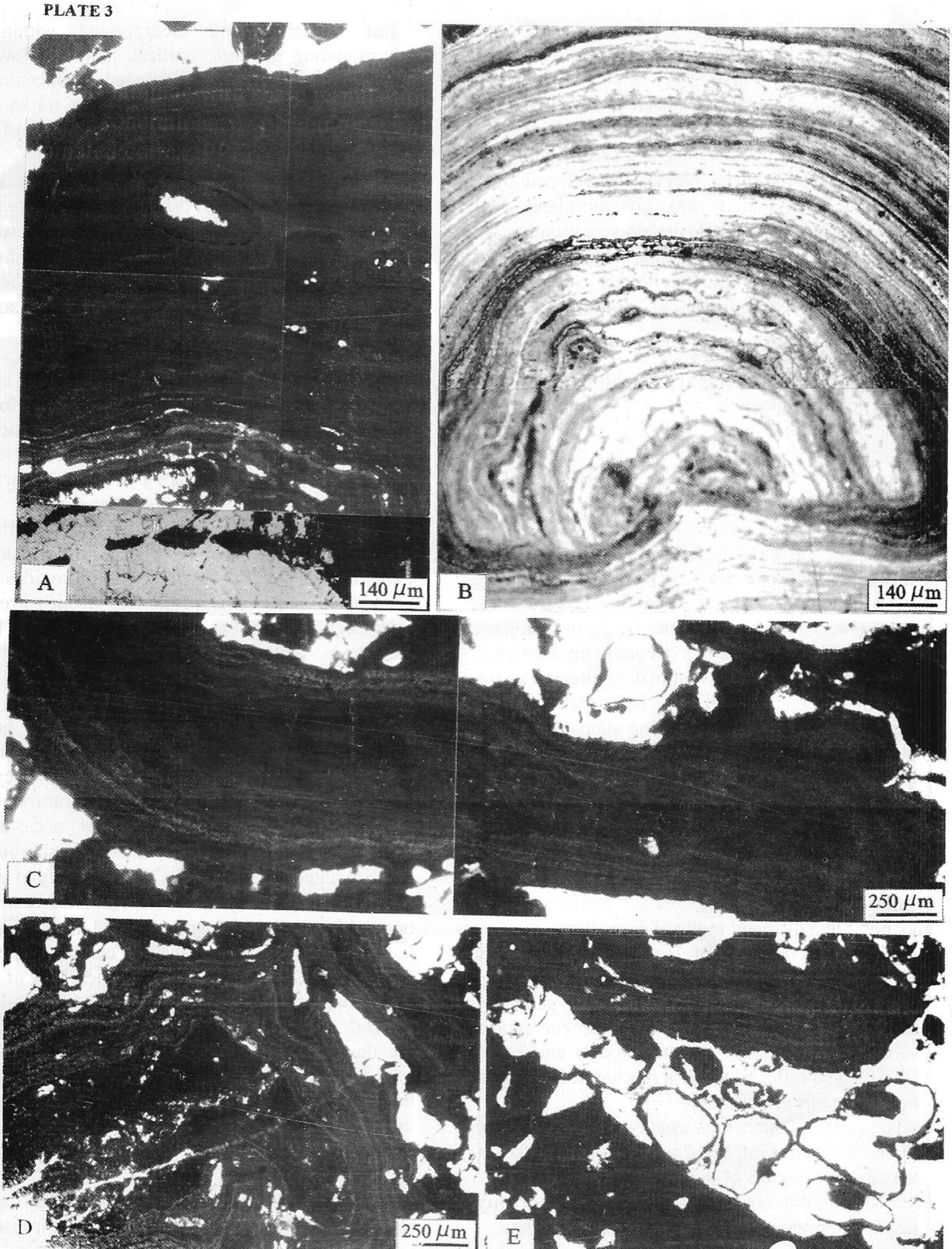
II. Ironstone Facies Types

The Lutetian ironstones are essentially grain-supported facies with subordinate mud-ironstones and include the following rock types:

1. Pisolitized (algal-nummulitic) rud-ironstone (PANR)

This rock type with the lithofacies ooidal-oncoidal grain-ironstone is best developed only at the Eastern

PLATE 3



Pl. 3: Ferriferous coated grains. A) A part of large oncoid with irregular cortical laminae incorporating small ooids, PPL. B) A polished sec. of a large oncoid with a thick cortex of alternating dark and light primary laminae encrusting a core of pre-existing oncoid fragment, PPL. C) An elongate concretionary glaebule with corroded skeletal core and faintly laminated envelopes, PPL. D) Crinkled and convoluted cortical laminae with sharp terminations characterizing concretionary glaebules, PPL. E) A concretionary glaebule with a completely consumed nucleus and faintly laminated cortex, PPL.

Wadi section of El Gedida mine area. It constitutes the base (10-30 cm thick) of the lower nummulitic ironstone unit 2 (Fig.5). It has an erosive sole and its top is mantled with thin goethite hard crusts. In outcrops and polished slabs, the rock is characterized by light egg-yellow and dark brown bands (few mm to 5 cm thick, for each) displaying a low-angle depositional dip attitude.

Petrographically the rock is siliceous pack-ironstone. Its ferriferous allochems are mostly of rudite size and represented mainly by iron-mineralized and micro-bored nummulitic tests and algal remains with *in situ* formed ferriferous glaebules (Pl.1E). Peloids, cortoids and ooids are rarely observed. With few exceptions, most of the ferruginized skeletal particles are aligned parallel to each other and to the main inclined bedding planes. The ferriferous allochems are embedded in a dense cryptalgal (microbial) amorphous iron mud matrix showing ghosts of biogenic tubes, voids or filaments and exhibiting in parts subtle or crude lamination. Authigenic quartz and locally hematite are the main cementing minerals, which occlude most of the inter-and intra-particles pore spaces, and replace selectively many parts of the allochems and matrix.

2. Ooidal-oncoidal grain-ironstone (OOnG)

It is intertonguing with the facies type nummulitic oncoidal pack-ironstone, and both form together three distinct lenticular ironstone bodies (Fig.5). Each body ranges in thickness from 40 cm to 1m and is separated from each other by a thin discontinuous layer or laminae of mud-ironstone facies. In outcrops, the ooidal-oncoidal ironstone beds have a characteristic egg yellow colour and conglomerate nature. They are internally massive without any sign of organization, except their irregular and scouring soles.

Microscopically, the rock is very poorly sorted siliceous grain(iron)stone displaying a remarkable bimodal grain size of gravel and sand grades. It consists essentially of ferriferous oncoids and ooids admixed with few peloids and worn ferruginized bioclasts mostly of large forams, skeletal algae and echinoderms (Pl.4A). These allochems are chaotically oriented and have tangential- and long-grain contacts. Some interstitial voids contain brecciated patches and clots of brown amorphous ferruginous mud matrix.

The majority of oncoids has a diameter ranging between 0.5 to 1 cm and rarely exceeds 2 cm, while ooids and peloids are of 1 mm or less in size. The oncoids and ooids are sub-spherical to discoid in form, and are composed of amorphous Fe-oxyhydroxides and goethite. The rock voids and non-tectonic cracks are filled with authigenic cement of reddish yellow goethite and quartz. The goethite cement envelops and links the framework allochems, giving a polygonal fitting fabric. Discrete patches of authigenic hematite crystals crosscutting and partially replacing the coated grains are frequently observed.

3. Nummulitic-oncoidal pack-ironstone (NOnP)

This facies possesses nearly the same allochem assemblage and cements of the intertonguing rock type OOnG, except it has a higher content of free (uncoated) Nummulitids, Assilins and echinoderm particles as well as a lesser amount of ooids. The rock is also finer in grain size, its allochems have a diameter ranging between 1 to 5 mm. The oncoids are mostly elongated and ellipsoidal in form with a thin concentric cortex (Pl.4B). The oncoids and the forams show parallel to subparallel and sometimes imbricate array and set in a dense amorphous ferruginousmud matrix. Megascopic and microscopic scouring surfaces armored with angular fragments of ooids, oncoids and bioclasts are observed.

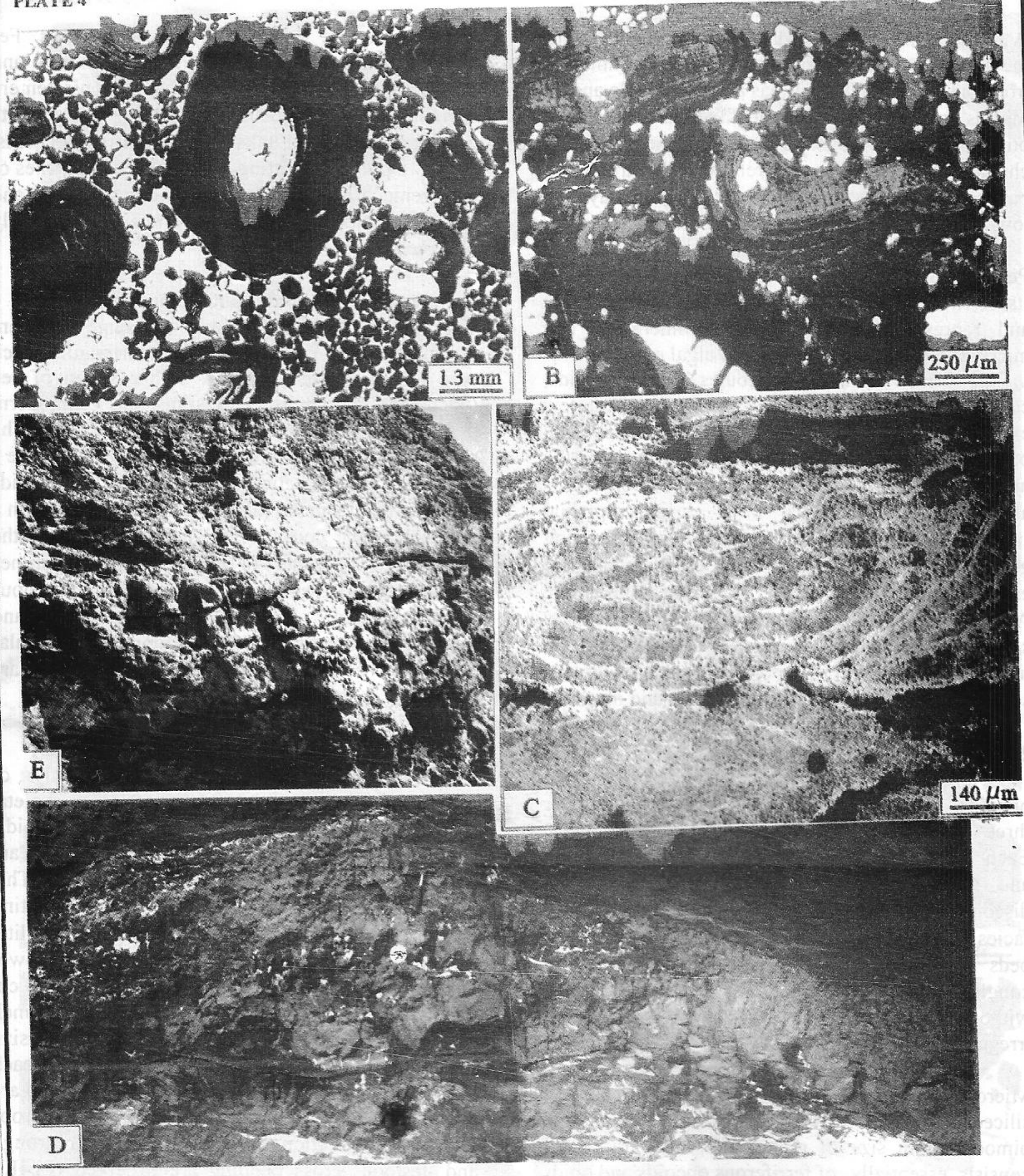
4. Ooidal -nummulitic grain-ironstone (ONG)

This grainstone facies consists mainly of ferruginized nummulitic tests and other skeletal particles mixed with few ferriferous ooids, cortoids, peloids and oncoids (Pl. 4C). The skeletal clasts are generally unworn and mostly *in situ* fragmented.This rock type is the most pervasive facies constituting most beds of the lower and upper nummulitic ironstone stratigraphic units (Fig.5). In the lower unit, it forms five to six megarippled beds (30-80 cm thick, for each) showing a remarkable lateral pinch and swell nature (Pl.4D). The successive megaripples overlap and sometimes truncate each other. They have sharp to scouring soles and are almost internally massive, except at few outcrops (e.g. El Harra section no. 7, Figs.1&4), where trough and festoon cross bedding are observed (Pl.4E). Some megaripples show an upward gradition in composition into peloidal- ooidal grain-ironstone facies, while in others, their troughs and flanks are filled or draped by lenses of ochreous red and yellow mud-ironstone. In most studied sections, this megarippled ONG facies are masked by pedogenetic features and precipitates.

5- Peloidal-ooidal grain-ironstone (POG)

This lithofacies type occurs as thin layers or laminae intertonguing and capping the above ONG facies, and forms commonly the top surface of the

PLATE 4



Pl. 4: Ironstone facies types. A) Ooidal-oncoidal grain(iron)stone displaying a distinct bimodal grain size, PPL. B) Nummulitic-oncoidal pack(iron)stone consisting of sub-parallel ferruginized *Nummulites* and elongate ferriferous oncoids, PPL. C) A polished sec. of ooidal-nummulitic grain(iron)stone being mostly composed of ferruginized nummulitic tests, PPL. D) A well-preserved megaripple bedform that swells and pinches laterally. E) A trough cross-bedded nummulitic ironstone being best preserved at El Harra mine section.

megaripples. It is best recorded in El Harra section. The rock is well sorted and grain-supported, consisting essentially of ferriferous ooids, cortoids and peloids with worn bioclasts of large forams and echinoids. Pervasive silica cementation with partial to complete replacement of most ferriferous allochems is common feature. The authigenic silica is in the form of micro- to coarse-crystalline quartz showing a granular mosaic texture.

5. DEPOSITIONAL ENVIRONMENT

There is a common agreement that the ooidal and pisoidal ironstones could occur in both marine and non-marine sedimentary environments (Siehl and Thein, 1989). For marine ironstones, different bathymetry and hydrodynamics, ranging from low energy (e.g. Knox, 1970 and Gygi, 1981) to agitated regime (e.g. Hallam, 1975; Germann, *et al* 1987; Siehl & Thein, 1989; El Aref *et al.*, 1996) have been suggested. The oolitic ironstones are also considered to accumulate either during a transgression (e.g. Van Houten and Purucker, 1984; McGhee and Bayer, 1985 and Young, 1989b) or during a regression (e.g. Hallam and Bradshaw, 1979; Teyssen, 1989) or during both states (e.g. Gehring, 1989 and Burkhalter, 1995).

In the study case of the Lutetian ironstones, the preponderance of ferruginized skeletal remains of typical marine fauna, side to side with ferruginous-coated grains mostly with bioclastic cores, provide a concrete evidence for a fully marine origin. Also, the nearly absence of any calcareous oncoids, pisoids with rare ooids from the equivalent carbonates confirms that the recorded ferriferous coated grains are plausibly primary depositional products. They neither inherited calcareous coated grains that were subsequently replaced by iron bearing solutions (e.g. Gheith, 1959; El Hinnawi, 1965; Basta and Amer, 1969, among others) nor lateritic pisoids and ooids derived from hinterlands and reworked in the Lutetian sea (Siehl and Thein's model, 1989). The invalidity of these origins could be supported by the general low content of Al in the examined oolitic and oncolitic ironstones (the Al2O3% from XRF analysis is 0.4-0.8). According to Maynard (1986) the scarcity of Al conent in the goethitic and hematitic ooids indicates that the soil origin of ironstone ooliths is unlikely.

The depositional environments of the concerned ironstones (ores) are previously interpreted as lacustrine (Ball and Beadnell, 1903), lagoonal facies (Said and Issawi, 1964) or shallow marine (El Aref *et al,* 1999). There is no discrimination of the effective depositional processes, conditions and mode and sites of formation and accumulation. These parameters are interpreted as follow:

The facies analysis revealed two main assemblages of original ironstone facies; grain-supported facies and mud-ironstones. The former association is the more pervasive and shows distinct depositional criteria arising from its components of ferriferous allochems, and the preserved depositional fabrics, and structures.

The allochems, particularly the fossil particles are abundant and diversified. They comprise nummulitids, alveolinids, other forams, echinoids, algae and mollusks. Ecologically, this assemblage indicates open and normal marine conditions (Wilson, 1975). The nummulitids, which are the main fossil allochem in all facies may have originally lived on a relatively soft muddy substrate (Girgs and Hindy, 1973) and its development is optimal in well aerated, warm and shallow marine water (Blondeu, 1972). However, the bio- and rock-fabrics are almost of grain to packstone nature and the tests, in many parts, accumulated in pockets with local edge-wise imbrication. These features indicate that a considerable amount of the mud had been winnowed away with a reworking of the large forams and the other bioclasts. The general moderately sorting of almost all-nummulitic ironstone facies may suggest that the reworking occurred *in situ* without large-scale transport. According to Futterer (1982), only a moderate current velocity (18 - 77 cm/sec) could rework nummulitic tests. These locally reworked fossil allochems represent parautochthonous grains (Seilacher, 1982). Such favorable conditions of prolific development and *in situ* concentration of *Nummulites* are likely to predominate on the top of submarine swells subjected to episods of hydrodynamic forces as storms (Blondeau, 1972; Aigner, 1983&1984).

The reworking and accumulation of nummulitic ironstone facies under storm action can be confirmed from its distinct megaripple bedform (Pl. 4D). The formation of megaripples is attributed to *in situ* reworking of largely parautochthonous debris by storm waves (e.g. Aigner, 1983 & 1985; Leckie, 1988 and Simpson and Erickson, 1990) or by a storm- induced unidirectional flow (e.g. Kelling and Mullin, 1975).

The second essential allochems of the grain-supported ironstone facies are the ferriferous

oncoids and ooids. Whereas the ferriferous oncoid is commonly accepted as biogenically accreted grain, different hypotheses concerning the origin of ooids and micro-oncoids are proposed. These comprise: a) a metasomatic replacement of calcareous ooids by iron-rich solutions (e.g. Gheith, 1959; Basta and Amer, 1969; and Kimberly, 1978 & 1979); b) an *in situ* diagenetic growth in lateritic vadose and hydromorphic environments (Nahon *et al*, 1980; Nahon, 1991 and Siehl and Thein, 1989); c) a synsedimentary formation by adsorption process in a condensed facies (Gehring, 1989), or by a mechanical accretion of Fe-Al-Si colloids and clay minerals followed by iron oxides transformations (e.g. Bhattacharyya and Kakimoto, 1982; Van Houten and Purucker, 1984; Germann *et al*, 1987; El Aref *et al*. 1996)); d) an intrasedimentary growth in an open-marine mud under fluctuating oxidizing bottom water and mildly reducing sub-bottom conditions (Gygi, 1981); and e) a biological accretion in different microbial mats of either algae, aerobic- and anaerobic- bacteria or fungi (e.g. Gattral *et al*, 1972; Dahanayake *et al*., 1985 and Dahanayake and Krumbien 1986). Many of these biogenic and abiogenic mechanisms converge to the opinion that, the formational conditions and processes may differ from those of the end-depositional sites. Also, the effective but not violent water movement that just able to turn the grains is considered as a prerequisite for a concentric growth of ferriferous ooids and oncoids.

In the examined ironstone facies, the ferriferous ooids are intimately associated with oncoids, and both are identical in mineralogy, morphology and internal architecture. These may strengthen the biogenic origin of the ferriferous ooids, but does not exclude the adsorption or mechanical processes. The biogenic role is substantiated by the wavy and overlapping nature, sometimes with club-shaped microstromatolitic structure of the cortical laminae as well as by the presence of the ferruginized algal remains, fine filamentous network and other problematic microbial structures (Pls.1E & 2A-C).
The association of the ferriferous ooids and oncoids with the ferruginized nummulitids and other fossils, occurring as free particles and nuclei indicates its growth and accumulation occurred on the sediment surface in an oxygenated environment. The observed internal truncation and overlapping between cortical laminae, which in some oncoids incorporate small ooids and ooid fragments point to an intermittent erosion and renewed encrustation. Such intrapaticles erosion as well as the grain-supported fabric of the ooidal-oncoidal ironstone facies suggests a reworking and concentration of the coated grains under an episodic agitated water or storm condition. The reworking seems to have been *in situ* without a significant transportation as attested by the poorly sorting with a distinct bimodal grain size and minor breakage of grains (Kreisa and Bambach, 1982). However the massive-bedding nature, with chaotic and jostle grain organization may reflect that, the final deposition of the ooidal-oncoidal facies was rapid, probably after sudden fall of storm wave or current action. On the other hand, the sandy sized and sorted ooidal-peloidal grain-ironstone laminae topping the megarippled nummulitic ironstone suggest a deposition under a waning storm condition.

Concerning the mud-ironstone rock type, its overall fine grain-size, mud-supported fabric and massive- to faint-laminated bedding, all refer to a deposition from suspension under a general calm water condition. The local occurrence of flaser and small-scale ripple cross lamination indicates an episodic current or wave action and the shallow nature of the depositional site. Considerable periods of subaerial emergence had been occurred as indicated by abundant desiccation, rhizoconcretions and other pedogenetic features. The characteristic lenticular intertonguing between the mud-ironstone and the kaolinitic mudstone may reflect the heterogeneous clastic composition of the source rocks.

Summing up, the original Lutetian ironstones (ores) had been accumulated on submarine swells (the wrench-related Cenomanian swells) under well-aerated and intermittent agitated and quiet water conditions. The grain-supported (nummulitic, oncolitic and oolitic) rock types represent a subtidal shoal facies that were formed, reworked by current and deposited under effective hydrodynamic force like tides or storms. The stormy events were interrupted by considerable periods during which the depositional sites were very shallow to partly emerged peritidal areas with relatively quiet hydrodynamics. Under these conditions the fine-grained mud-ironstone and siliciclastic were deposited and subjected to pedogenetic processes. The original marine oolitic-oncolitic and nummulitic ironstone facies associations are highly disturbed and obliterated as a result of the intra-Eocene karstification inducing lateritization and pedogenesis and formation of intra-karstic lateritic precipitates (El Aref and Lotfy, 1989; El Aref, 1994 and El Aref *et al*.1999).

6. DEPOSITIONAL EVOLUTION AND GENESIS

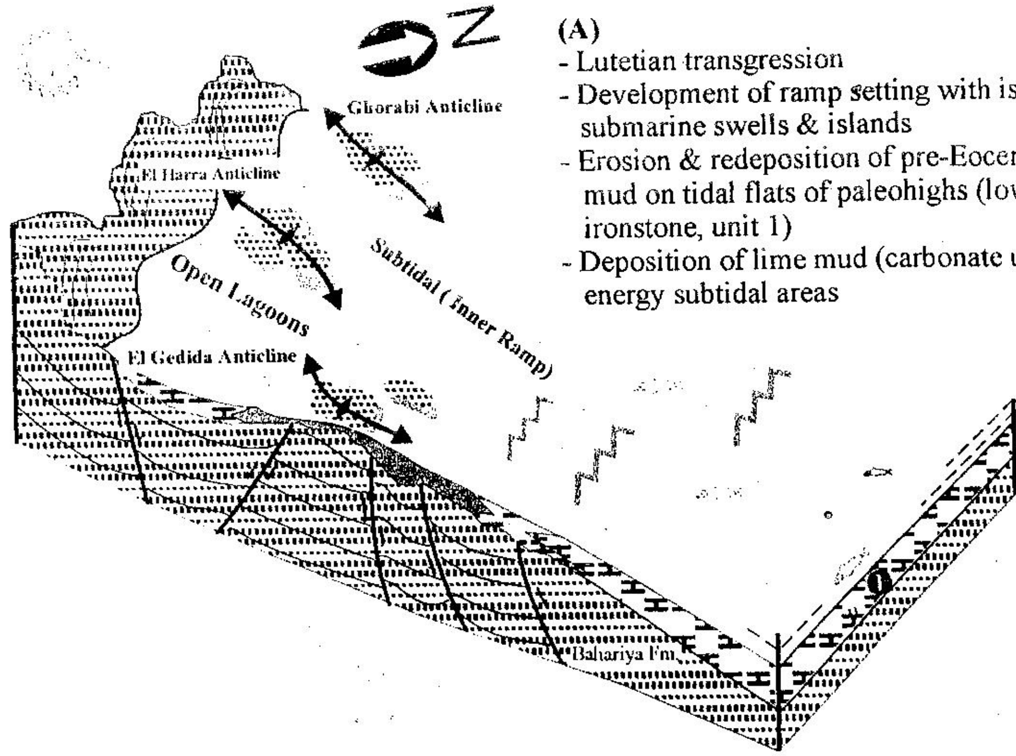
From the above stratigraphic and sedimentologic data, it is clear that the facies hierarchy of the original Lutetian ironstone deposits forms two distinct facies sequences, being separated and delineated by unconformity (Fig.5). Each sequence shows a coarsening-upward tendency. It starts with tidal flat mud-ironstone with siliciclastics, overlain by coarse-grained nummulitic, oncolitic and oolitic shoal ironstone facies being terminated with paleosol horizon. The equivalent thick carbonate succession displays also a similar facies organization forming two coarsening-upward sequences, being locally separated by a well-developed paleokarst surface (Fig.2). Each carbonate sequence begins with lagoonal/peritidal lime-mudstone, grading above to subtidal facies of nummulitic wackestone to grainstone. The nummulitic limestone facies seems to be deposited under relatively quiet hydrodynamic conditions in contrast with its equivalent nummulitic ironstone facies. This can be evident by the intensive bioturbation characterizing the nummulitic limestone facies. The discontinuous and thin karstic soil ferruginous deposits superimposed on the nummulitic limestone reflect the shoaling to subaerial exposure at the end-depositional stage of the carbonate facies sequence.

The depositional evolution of the Lutetian carbonate and ironstone facies sequences in El Bahariya region and the factors controlling its development and distribution can be summarized as follow:

1) With the beginning of Middle Eocene time, sea drowned the Bahariya paleohigh that was tectonically standing as positive blocks subjected to intensive denudation and pedogenesis since Late Cretaceous time. Consequence to such transgression, an inner ramp setting for carbonate deposition was developed but with isolated submarine swells and islands of domal and double plunging anticlines of Cenomanian clastics, enclosing abundant ironstone and glaucony bands (Fig.6A). These swells (e.g. Ghorabi, El Harra and El Gedida anticlines) are nearly aligned along NE-wrench faults that were active during Late Cretaceous and occasionally re-activated during the Eocene times (Sehim, 1993; IEP, 1993-1997; El Aref *et al.*, 1999).

2) In the early stages of the inner ramp deposition, open lagoons were developed in the low-lying inter-swell areas (Fig.6A). The swell areas, of which parts were probably emerged, formed very shallow tidal flats. Upon these currently emerged tidal flats, iron-rich mud and colloids with siliciclastics derived from the Cenomanian clastics and laterites are redeposited from a suspension and constituted the lower mud-ironstone unit (Fig.6A). In the mean time, within the subtidal lagoons that received little or no-clastics, thin- to thick-carbonates of slightly bioturbated lime-mudstone are deposited. Its variation in thickness is also related to the paleorelief of the underlying Bahariya Formation. Along the transitional sites between the swells and the low-lying lagoonal areas, mixed facies consisting of iron-rich marl and mud-ironstone are formed (e.g. in Naqb Ghorabi section no.1 and bore hole no.6, Figs.1&3).

3) An advance and a rise of the Lutetian sea level had been continued and the ramp setting became ecologically a favorable habitat for nummulitids, alveolinds, echinoids, bivalves and gastropods. In the subtidal inter-swell areas, bioclastic alveolinds/nummulitids limestone facies accumulated under oscillating storm wave base with intensive biogenic burrowing (Fig.6B). On the contrary, the submarine paleohighs were subjected to high hydrodynamic forces; storms and/or tidal currents. These resulted in scouring of the sea bottom iron-rich muddy substrates with *in situ* reworking and concentration of the large forams and other skeletal grains (Figs.6B&7A). In addition, the net sedimentation rate was minimal to negligible. This is evident by the presence of the ferruginous microbored bioclasts, concentration of the fossils and very fine ferruginous encrustations (Gehring, 1989; Kidwell, 1991 & Burkhalter, 1995). In such environments of minimal net sedimentation, authigenic iron minerals would be able to develop and concentrate (Gattral *et al.* 1972). Compounds of silica-rich amorphous iron oxyhydroxides or ferrihydrites were increased in the depositional medium of the paleohighs. These were most probably derived as colloids from the underlying iron- and glaucony-bearing Cenomanian clastics either via surface or subsurface flows (Fig.7A). The iron compounds had infiltrated and adsorbed into the inter-and intra-particles pore spaces. This process is assisted by microboring organisms. Subsequently, the calcareous fossil particles were firstly stained and gradually replaced by the infiltrated amorphous iron (Figs.7&8). The resultant ferruginized fossils provide a mobile substrate for iron-encrusting organisms (e.g. algae/bacteria) to develop ferriferous oncoids and ooids. The accretion of the ferriferous-coated grains was controlled by the hydrodynamic regime of the medium (Fig.9). It flourished during the intermittent weakly agitated but not stagnant conditions (inter-storm events)



(A)
- Lutetian transgression
- Development of ramp setting with isolated submarine swells & islands
- Erosion & redeposition of pre-Eocene lateritic Fe mud on tidal flats of paleohighs (lower mud ironstone, unit 1)
- Deposition of lime mud (carbonate unit 1) on low energy subtidal areas

(B)
- Continuous transgression & rise of sea level
- Shoaling, storm action, reworking & low rate of sedimentation upon drowned paleohighs
- Concentration of skeletal particles; active iron depositing microbs; ooids & oncoids formation
- Megaripple generation & accumulation of the lower nummulitic ironstone (unit 2) and the subtidal nummulitic carbonate (unit 2)

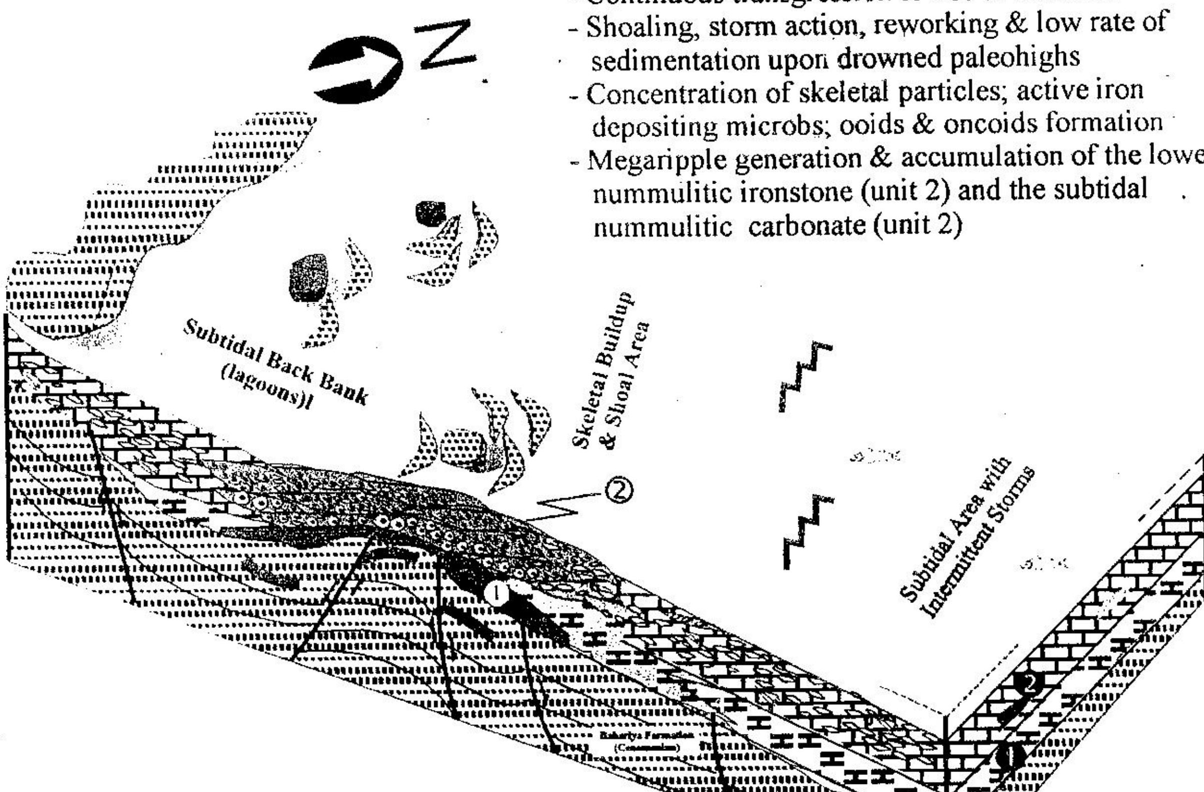
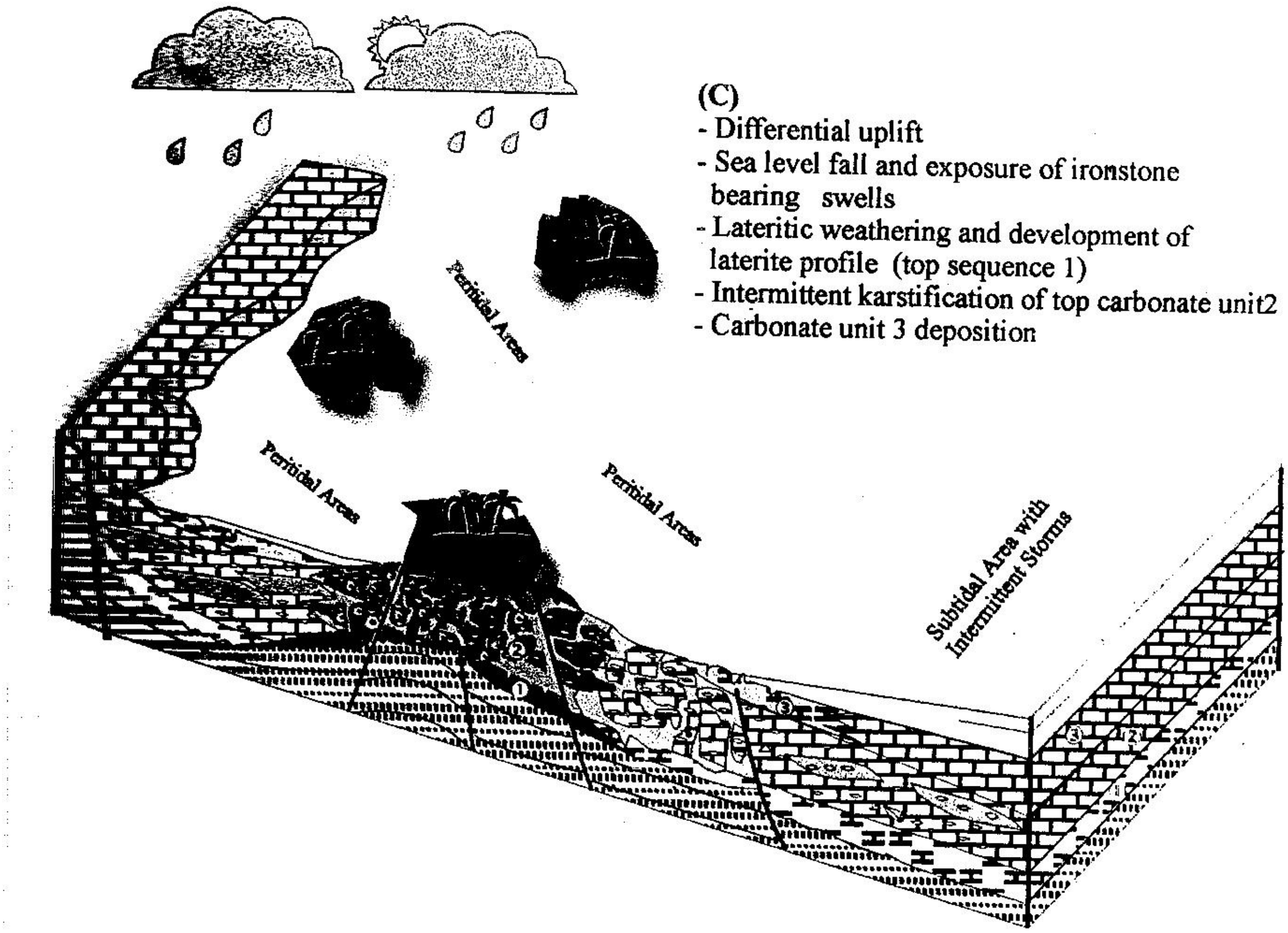
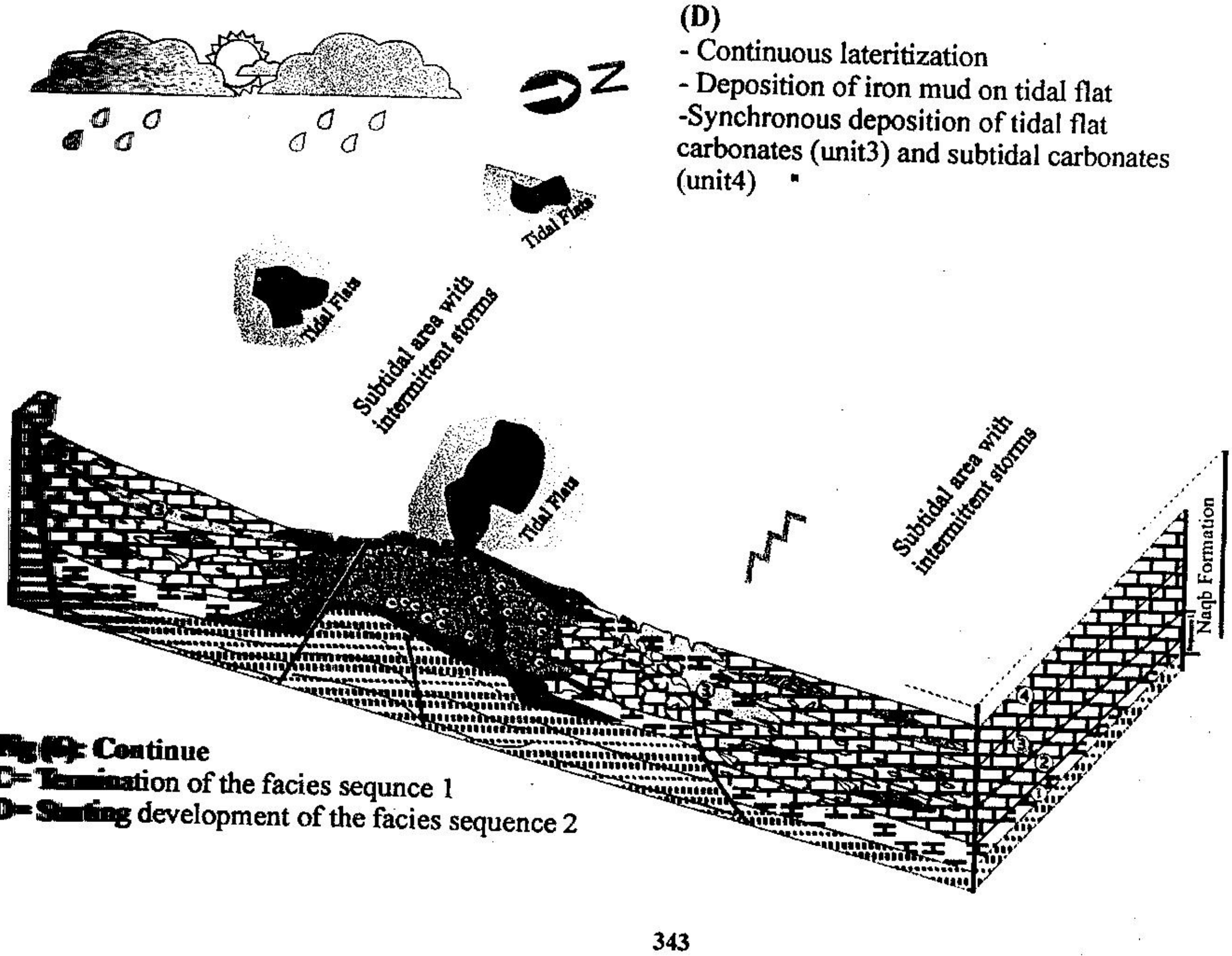


Fig. (6): Depositional Evolution and Development of Lutetian Carbonate and Ironstone Sequences.
A & B= Development of the Lower carbonate and ironstone facies sequences.



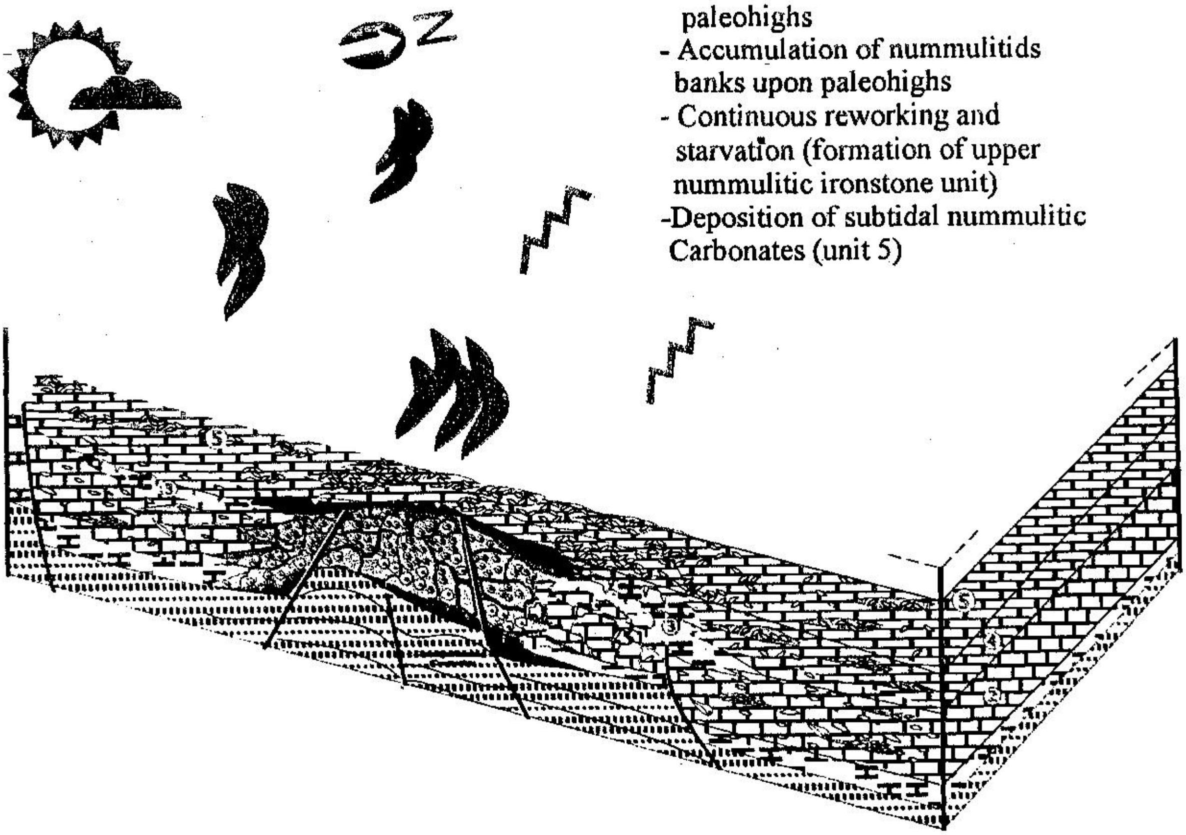
(C)
- Differential uplift
- Sea level fall and exposure of ironstone bearing swells
- Lateritic weathering and development of laterite profile (top sequence 1)
- Intermittent karstification of top carbonate unit2
- Carbonate unit 3 deposition

(D)
- Continuous lateritization
- Deposition of iron mud on tidal flat
-Synchronous deposition of tidal flat carbonates (unit3) and subtidal carbonates (unit4)



[redacted] Continue
C= [redacted]ion of the facies sequnce 1
D= [redacted] development of the facies sequence 2

(E)
- Renewed sea transgression upon paleohighs
- Accumulation of nummulitids banks upon paleohighs
- Continuous reworking and starvation (formation of upper nummulitic ironstone unit)
- Deposition of subtidal nummulitic Carbonates (unit 5)



(F)
- Local uplifting, subarial exposure
- Karstification & lateritic pedogenesis upon exposed carbonates and ironstones
- Deposition of glauconitic shale and marl And fossiliferous limestones of the Hamra Formation

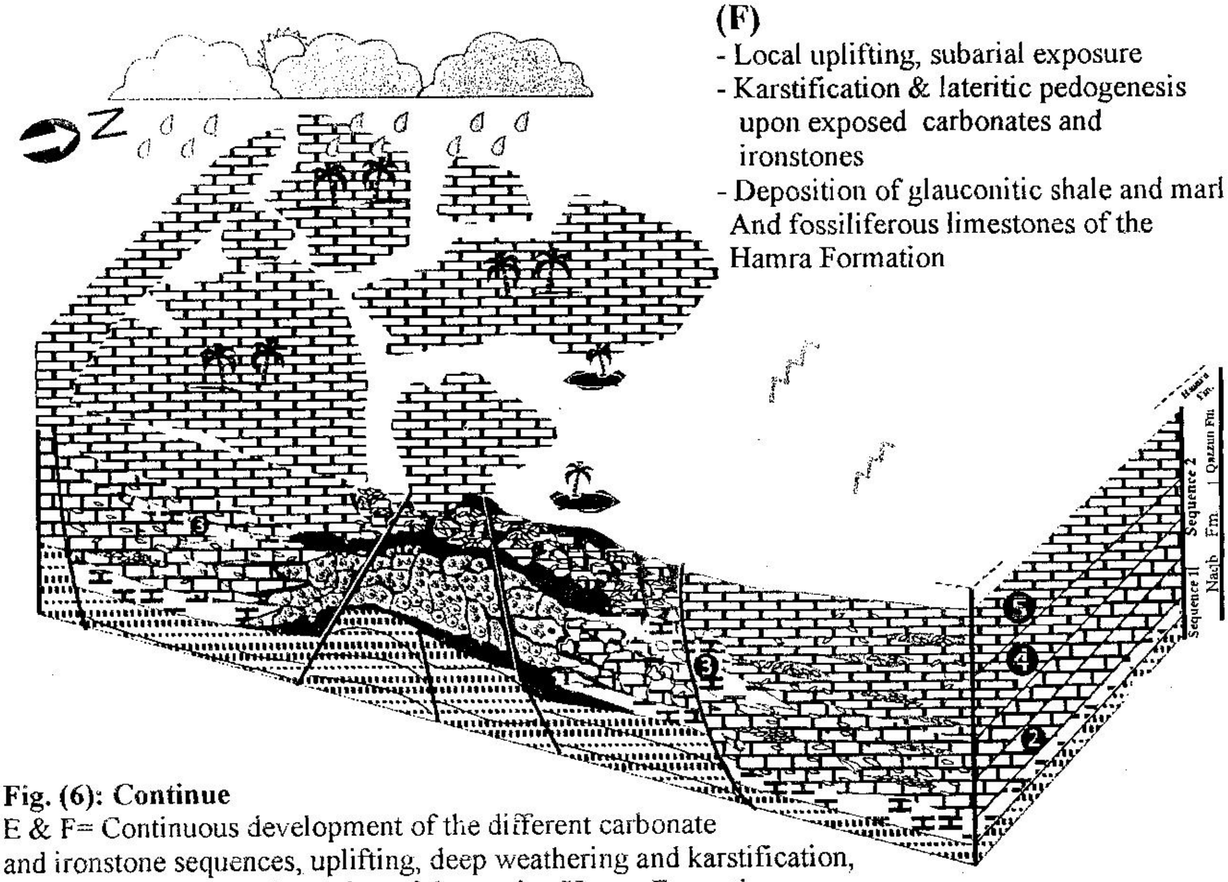
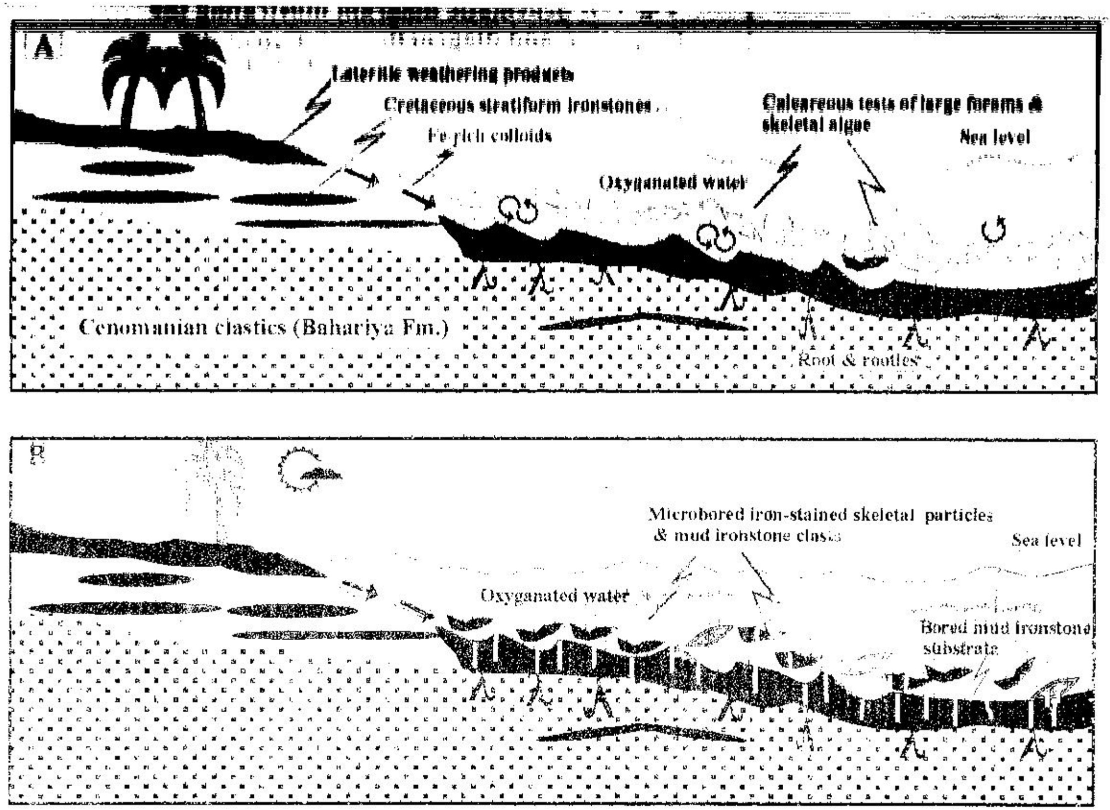


Fig. (6): Continue
E & F= Continuous development of the different carbonate and ironstone sequences, uplifting, deep weathering and karstification, sea transgression and formation of the marine Hamra Formation

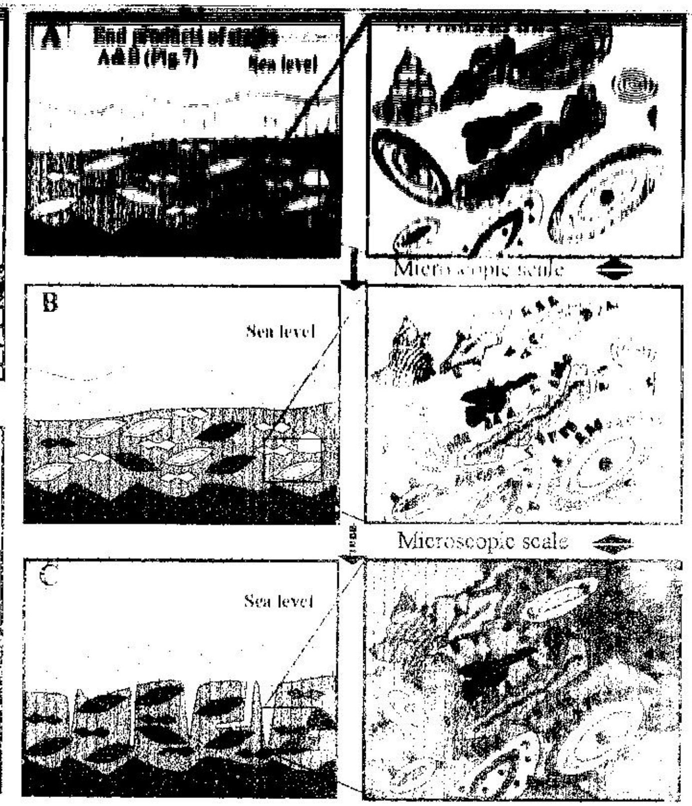


(A): Scouring of Fe mud substrata; winnowing of mud; concentration of parautochthonous calcareous particles (mainly large forams & algae with reworked ironstone clasts)

(B): Continuous reworking; intermittent debouching of Fe-rich colloids; starvation; intensive microboring; concentration of amorphous iron oxyhydrates rending skeletal particles and partially filling intra- and inter-particles pores; staining and replacement of skeletal grains by limonite and fibrous goethite.

The conditions and processes of stages A & B are currently repeated and their synsedimentary iron-mineralized products are the main allochems constituting the different nummulitic, oolitic & oncolitic ironstone facies.

(Fig.7): Schematic Diagram Demonstrating Synsedimentary Development Of Ferrifirous Particles (Skeletal & Non-skeletal).

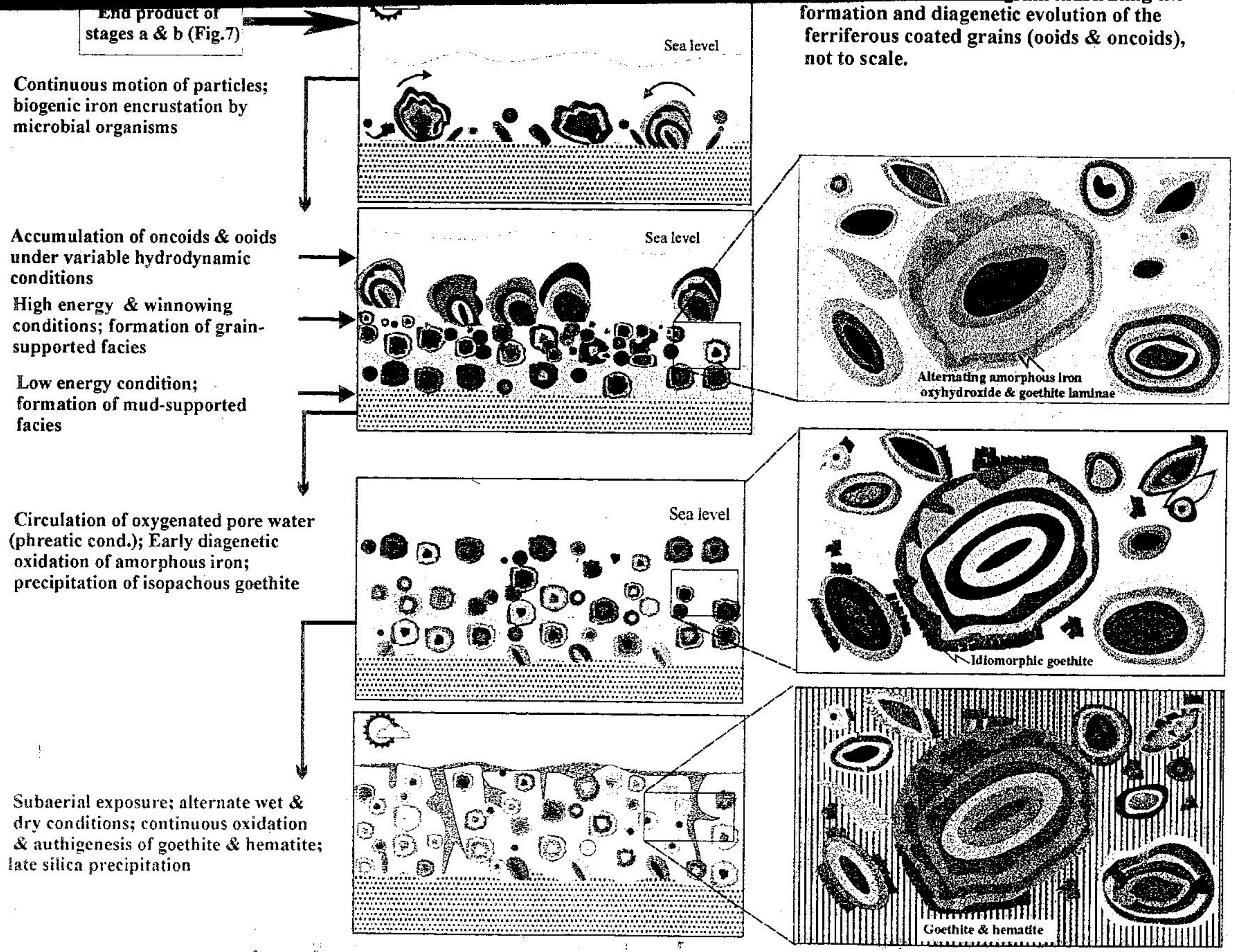


(A): Accumulation under agitated water and storm condition; grain-supported bioclastic nummulitic ironstone rich (limonitic) skeletal particles.

(B): Continuous deposition ; circulation of oxygenated pore water; early diagenetic goethite, replacing amorphous Fe hydroxides and filling intra particles pores; precipitation of isopachous authigenic goethite in inter- particles voids; release of silica.

(C): Subarial exposure (karstification & pedogenesis); brecciation and encrustation by redeposited colloform goethite and hematite and deposition of late quartz and calcite cement (not to scale).

Fig. (8): Schematic Diagrams Showing The Development Of Bioclastic (algal) Nummulitic Ironstone Facies From The End Products Of Stages A & B Of Figure 7.



formation and diagenetic evolution of the ferriferous coated grains (ooids & oncoids), not to scale.

and is probably hampered or hindered during the storm periods. Accordingly, the percentage of the coated grains to the free (uncoated) ferruginized fossil particles was intimately relied on the duration of the favorable conditions of the biogenic accretion. Repetition of these processes and conditions under a general low rate of sedimentation resulted in the accumulation of condensed ironstone deposits of the lower grain-supported (oncolitic-oolitic-nummulitic) ironstone unit. Soon after deposition, the accompanied decay of the organic matters could change the Eh toward a relatively reducing condition in the sub-bottom sediments. This condition with the reaction between iron-rich particles and pore water may lead to a concentration and mobilization of ferrous iron in pore solution and release of silicic acid.

4) After the accumulation of the lower nummulitic-oolitic ironstones and its equivalent nummulitic carbonate unit, a significant fall in the Lutetian sea level occurred (Fig.6C). It was most probably related to a local tectonic movement via re-activation of the NE wrench faults and the accompanied NW extensional faults. A consequence to such intra-Lutetian sea level fall, the swell areas were almost completely emerged. Its cover of ferriferous sediments was subjected to a subaerial weathering and a lateritic pedogenesis (El Aref andLotfy, 1989 and El Aref *et al.*1999). These processes led to the dissolution of any remnants of the original calcareous sediments and the formation of dissolution cavities; dehydration and partial transformation of amorphous iron oxyhydroxides of the ferriferous allochems to goethite and locally hematite; desiccation, bedding collapse and brecciation; local glaebulization and formation of orthic ferriferous pisoids; local growth of discrete kaolinitic and alunitic nodules, and successive formation of the various authigenic minerals. In a nearly paragenetic order, the authigenic minerals include:

a) Crustified goethite and hematite, which recoated and linked the ferriferous allochems in a polygonal fitting fabric or encrusted the crackled and collapse breccia forning cockade structure.
b) Authigenic quartz in the form of inequicrystalline mosaic texture of fine to coarse crystals. It occluded many of inter- and intraparticles pores and voids as well as partially replaced the surrounding allochems. In some beds of El Harra ironstone deposits pervasive silicification left traces and ghosts of the ferriferous allochems.
c) Poikilotopic hematite cements, which has an erratic distribution and partially to completely digests the ferriferous allochems and quartz cement. A high-grade massive hematitic ore is recorded at the High Central area (topographic name) of El Gedida mine. It is formed via an intensive replacement and masking of the original grain-supported ironstone facies by this poikilotopic hematite.
d) Authigenic ramanechite precipitated as long needle crystals that grew in a radial form from a single point and occupied isolated vugs and cavities.
e) Authigenic barite filled fractures and discrete voids. Some voids are large and occupied by rosette-like pockets of giant barite crystals, which are economically quarried.

The above pedogenetic and diagenetic features and related mineral paragenesis suggest fluctuating vadose and phereatic diagenetic environments and alternating humid and dry climatic conditions. Concomitant with the lateritic alteration and iron-concentration upon the exposed swell areas, the adjacent nummulitic carbonate deposits were also emerged and subjected to karst weathering processes (Fig.6C). However the emergence was intermittent or short-lived as envisaged by the intertonguing or alternation between the thin karst soil deposits and marine carbonates (as on top unit 2 and in unit 3).

5) A renewed rising of the Lutetian sea level and re-drowning of the exposed inner ramp subenvironments occurred (Figs.6D&E). The depositional, diagenetic and pedogenetic conditions and processes that prevailed during the stages 1-4 were repeated in a nearly similar order. These developed the upper facies sequence of both carbonate and ironstone successions (sequence 2 in Figs.2 &5). However, it seems that, the carbonate sedimentation in the submerged inter-swell areas was preceded without a significant interruption, while the swell areas were currently emerged and the net sedimentation rate was low. This is indicated by the thick accumulation of carbonate facies (carbonate units 3,4&5, Figs.2&6F) in comparison with the synchronous very thin ironstone deposits upon the paleohighs (ironstone units 3&4, Figs.5&6F).

7. CONCLUSIONS

1) Different ages and modes of formation have been proposed for the study ironstones (ores) of El Bahariya region. The present study provides concrete evidences that these ironstones were completely developed during the Middle Eocene. In El Gedida and El Harra areas, conglomerate and oxidized glaucony deposits of El Hamra Formation (Late Eocene) unconformably overlie the ironstone

succession. Such unconformable relationship with an irregular contact and suprajacent conglomerate consisting mainly of locally reworked ironstone gravels, substantiate that the ironstone (ore) deposits were formed, exposed and subjected to erosion at least prior to Late Eocene age.

2) The restricted distribution and discrete occurrences of the study ironstone deposits in a limited stratigraphic interval (Middle Eocene) can be simply explained in the context of a deposition and diagenesis under synchronous effect of different sedimentary conditions, sediment supply and net rate of sedimentation.

3) The Lutetian ironstone deposits represent a reduced (or condensed) depositional product and a facies change of the laterally equivalent thick carbonate succession.

4) The carbonates and equivalent ironstone deposits were generally developed along an inner ramp setting but under different depositional, diagenetic and pedogenetic conditions and processes. The ironstones were accumulated upon submarine swells of Cenomanian clastics. The deposition occurred under conditions swinged between agitated shoal water with continuous reworking via storm and/or tide actions and a very shallow, current-emerged and quiet tidal flat regime. The equivalent carbonate facies were deposited in the inter-swell areas and under subtidal to intertidal conditions with oscillating storm wave base.

5) The numerous bands of ironstones and oxidized green sands of the exposed and submerged Cenomanian Bahariya clastics represented the main source of iron for the Lutetian oolitic ironstone formation. Silica rich amorphous iron oxyhydroxides and/or earthy goethite with minor Mn and Al were derived probably as colloids from the Cenomanian clastics and debauched into the Lutetian sea via surface and subsurface flows. According to Harder (1989), goethite, hematite and quartz can crystallize from silica bearing amorphous iron oxyhydroxides either under oxidizing conditions or if the Si /Fe ratio is low. The preservation of amorphous iron oxyhydroxide in the ferruginized bioclasts, in the cortical laminae of the coated grains and in the bands of mud-ironstones supports the assumption that it was the precursor iron material.

6) A minimum rate of net sedimentation upon the submarine swells, hydrodynamic and the activity of microbial organisms played the essential role in the concentration, trapping and encrustation of iron and production of the different ironstone facies and the associated ferriferous allochems.

7) Intra-Eocene uplifting, exposure and karstification phases inducing lateritization and pedogenesis led to the destruction of the original marine ironstone facies and accumulation of lateritic iron-rich products and ore conglomerates.

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الوضع الترسيبي وأصـــل تكوين تتابعات الحجر الحديدي السريائى و الأونكوليتى (الايوسينى-اللوتاسى)، شمال منخفض البحرية، مصر

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الملخص

في الهضبة الشمالية الشرقية لمنخفض الواحات البحرية بالصحراء الغربية, مصر, يتواجد تتابع من رواسب خام الحديد السريائى و الأونكوليتى التابع لعصر الأيوسين الاوسط ومحدد بأسطح عدم توافق حيث يقع بين الصخور الفتاتية للعصر السينومانى والرواسب الجلوكونيتية التابعة لعصر الأيوسين الأعلى. تجمعت هذه الخامات الحديدية أثناء ترسيب الحجر الجيري لمكوني النقب و القــازون فـي المتحسر القاري لبحر اللوتاسي و ذلك على ارتفاعات تركيبية من طيات و قباب منفصلة من صخور مكون البحرية السينومانى. و يمثل تتابع خام الحديد قطاع ترسيبي مختزل و تغير سحنى يكافئ قطاع سميك من رواسب الحجر الجيري لمكوني النقب و القازون.

و قد أظهر التحليل السحنى و الوضع الترسيبي للرواسب الحديدية أنها تتكون من عدة ســحنات حديدية حبيبيــه و ســـحنات حديدية طينية تكررت في تتابعين متماثلين يفصلهما سطح عدم توافق تأثر بعوامل كارستية و لاتيريتية أدت إلى تغير في التركيب الأصلي للسحنات مع تركيز الحديد. يبدأ كل تتابع سحنى برواسب ضئيلة السمك من الحديد الطيني و الطين الكاولينى تكونوا تحت ظروف ترسيبية هادئة علـى مسطحات المد الشاطئية أو مستنقعات طينية ضحلة. يتلو السحنات الطينية وحدة ترسيبية من ســحنات حديديــة حبيبيــه غنيــة بحفريـــات حديديــة مثل الفورامينيفيرا (نيوميوليت و الفيولين) مع بعض الهياكل الطحلبية و بقايا من الرخويات و الجلد شوكيات مختلطة مع حبيبات مــن السريائيت و الأونكويد الحديدية تكونت أثناء الترسيب. وقد تجمعت هذه السحنات في مياه ضحلة تحت ظروف تتراوح من هائجة و عاصفة أحيانا إلى هادئة نسبيا مع تنقيح مستمر و ضئالة في الترسيب الإجمالي.

و تتكون السحنات الحديدية الطينية و الحبيبية في معظمها من أكاسيد الحديد المائية الغير متبلورة مع جيوتيت و هيماتيت بالإضافة إلى معــادن الكوارتز و الباريت و الجبس و أكاسيد المنجنيز.

وقد ناقشت وأوضحت الدراسة مصدر هذه الرواسب الحديدية و العوامل التي تحكمت في تكوينها و توزيعها واوضحت دور الكائنات الحيــة و العوامل الترسيبية فى تجميع الروسب الحديدية وتشكيل انسجتها الصخرية في نموذج ترسيبي متكامل.